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THE PALEOZOIC ROCKS FOUND IN DEEP WELLS IN WISCONSIN AND NORTHERN ILLINOIS[1]

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INTRODUCTION

The study of the Paleozoic formations penetrated by deep wells in Wisconsin and northern Illinois was begun by the writer in 1912, when the entire collection of samples of drill cuttings that had been collected from that area by the United States Geological Survey[2] was donated to the University of Wisconsin. Since that date the co-operation of many well drillers and engineers has enlarged the collection until it now includes over 8,000 specimens. Its study has been carried on in connection with work on the outcrops for the Wisconsin Geological and Natural History Survey, mainly under the direction of Dr. E. O. Ulrich, of the United States Geological Survey. In the last few years the State Survey has paid well drillers five cents for each sample with a minimum of $2.50 for each record; sample bags with attached labels are furnished. After study of the samples blue prints showing the geological section, casing log, water levels, yield, and other data are

[1] Published by permission of the state geologists of Illinois and Wisconsin.

[2] M. L. Fuller, E. F. Lines, and A. C. Veatch, "Record of Deep Well Drilling for 1904," *U.S. Geol. Survey Bull. 264* (1905), pp. 76–77. M. L. Fuller and Samuel Sanford, "Record of Deep Well Drillings for 1905," *U.S. Geol. Survey Bull. 298* (1906), pp. 176–79, 295–96.

furnished free to both owners and drillers. This policy, combined with visits to drillers in the field, has resulted in a constantly increasing percentage of good records of new wells.

The present paper is not intended to treat the subject of the paleontology nor to outline the history of the separation of the formations. For these subjects reference may be made to the works of Owen, Hall and Whitney, Wooster, Chamberlin, Strong, Irving, Hall and Sardeson, Sardeson, Ulrich, Walcott, Savage, Savage and Ross, Twenhofel and Thwaites, Alden, Bassler, and others.[1]

[1] D. D. Owen, *Report of a Geological Survey of Wisconsin, Iowa, and Minnesota*, Philadelphia, 1852. James Hall and J. D. Whitney, *Report of the Geological Survey of the State of Wisconsin*, Vol. I, 1862. G. A. Shufeldt, "On an Oil Well Boring at Chicago," *Amer. Jour. Sci.*, Vol. XL (1865), pp. 388–89. H. M. Bannister, "Cook County," *Illinois Geol. Survey*, Vol. III (1868), pp. 239–56; *Economical Geol. of Illinois* (1882), pp. 180–201; "Dekalb, Lake, and Other Counties," *Illinois Geol. Survey*, Vol. IV (1870), pp. 111–89; *Economical Geol. of Illinois*, Vol. II (1882), pp. 361–449. T. S. Hunt, "On the Oil-Bearing Limestone of Chicago," *Canadian Naturalist*, Vol. VI (1872), pp. 54–59. James Shaw, "Geology of Northwestern Illinois," *Illinois Geol. Survey*, Vol. V (1873), pp. 1–216; *Economical Geol. of Illinois*, Vol. III (1882), pp. 1–226. Moses Strong, "Geology and Topography of the Lead Region," *Geology of Wisconsin*, Vol. II (1878), pp. 668–88. R. D. Irving, "Geology of Central Wisconsin," *ibid.*, pp. 525–607. L. C. Wooster, "Geology of the Lower St. Croix District," *ibid.*, Vol. IV (1882), pp. 104–28. Moses Strong, "Geology of the Mississippi Region North of the Wisconsin River," *ibid.*, pp. 38–91. R. P. Whitfield, "Paleontology," *ibid.*, pp. 163–349, plates. T. C. Chamberlin, *Geology of Wisconsin*, Vol. I (1883), pp. 119–212. A. S. Tiffany. "Record of Deep Well at Dixon, Illinois," *Amer. Geol.*, Vol. V (1890), p. 124. C. W. Hall and F. W. Sardeson, "Paleozoic Formations of Southeastern Minnesota," *Geol. Soc. Amer. Bull.*, Vol. III (1892), pp. 331–68. J. A. Udden, "A Geological Section Across the Northern Part of Illinois," *Illinois Board of World's Fair Commissioners Report*, 1895, pp. 117–51. C. W. Hall and F. W. Sardeson, "The Magnesian Series of the Northwestern States," *Geol. Soc. Amer. Bull.*, Vol. VI (1895), pp. 167–98. F. W. Sardeson, "The Galena and Maquoketa Series," *Amer. Geol.*, Vol. XVIII (1896), pp. 356–68; Vol. XIX (1897), pp. 21–35, 91–111, 180–90; "Nomenclature of the Galena and Maquoketa Series," *ibid.*, Vol. XIX (1897), pp. 330–36. Stuart Weller, "A Peculiar Devonian Deposit in Northeastern Illinois," *Jour. Geol.*, Vol. VII (1899), pp. 483–88. F. W. Sardeson, "The Lower Silurian Formations of Wisconsin and Minnesota Compared," *Minnesota Acad. Nat. Sci. Bull.*, Vol. III (1901), pp. 319–26. C. W. Rolfe, "The Geology of Illinois as Related to Its Water Supply," *Illinois Univ. Chem. Survey of the Waters of Illinois*, 1903, pp. 41–56. H. F. Bain, "Zinc and Lead Deposits of the Upper Mississippi Valley," *U.S. Geol. Survey Bull. 294*, 1906; *Wisconsin Geol. and Nat. Hist. Survey Bull. 19*, 1907. U. S. Grant, "Lead and Zinc Deposits of Southwestern Wisconsin," *Wisconsin Geol. and Nat. Hist. Survey Bull. 9*, 1903; *Bull. 14*, 1906. C. P. Berkey, "Paleogeography of St. Peter Time," *Geol. Soc. Amer. Bull.*, Vol. XVII (1906), pp. 229–50. F. W. Sardeson, "Galena Series," *ibid.*, Vol. XVIII (1907), pp. 179–94. Stuart Weller,

The writer is greatly indebted to Dr. Ulrich for the inspiration which led to this study and for much unpublished information, and to Mr. F. W. DeWolf for opportunity to examine records from Illinois. The nomenclature and correlation of the formations here given is that proposed by Ulrich and the writer takes no responsibility for it as a number of features have not yet met with general acceptance.

"The Paleontology of the Niagaran Limestone in the Chicago Area: the Trilobita," *Chicago Acad. Sci. Nat. Hist. Survey Bull. 4*, 1907, Pt. 2, pp. 161–281; "The pre-Richmond Unconformity in the Mississippi Valley," *Jour. Geol.*, Vol. XV (1907), pp. 519–25. F. W. Sardeson, "The St. Peter Sandstone," *Minnesota Acad. Nat. Sci. Bull.*, Vol. IV (1910), pp. 64–88; "The Fauna of the Magnesian Series," *ibid.*, pp. 92–105. E. O. Ulrich, "Revision of the Paleozoic System," *Geol. Soc. Amer. Bull.*, Vol. XXII (1911), pp. 281–680. C. D. Walcott, "Cambrian Geology and Paleontology," *Smithsonian Misc. Coll.*, Vol. LII (1914), No. 13, p. 354 (gives section by Ulrich). G. H. Cox, "Lead and Zinc Deposits of Northwestern Illinois," *Illinois State Geol. Survey Bull. 21*, 1914. R. S. Bassler, "Bibliographic Index of American Ordovician and Silurian Fossils," *U.S. Nat. Museum Bull. 92*, 1915, Plates 2 and 3. G. H. Cady, "The Structure of the La Salle Anticline," *Illinois State Geol. Survey Bull. 36*, (1916), pp. 105–41. T. E. Savage and C. S. Ross, "The Age of the Iron Ore in Eastern Wisconsin," *Amer. Jour. Sci.*, Vol. XLI (1916), pp. 187–93. E. O. Ulrich, "Correlation by Displacements of the Strand-Line and the Function and Proper Use of Fossils in Correlation," *Geol. Soc. Amer. Bull.*, Vol. XXVII (1916), pp. 459–61, 477–78. T. E. Savage, "Alexandrian Rocks of Northeastern Illinois and Eastern Wisconsin," *ibid.*, pp. 305–24. G. H. Cady, "Geology of the La Salle and Hennepin Quadrangles," *Illinois State Geol. Survey Bull. 23*, (1917), pp. 55–65; "The New Richmond Sandstone of Northern Illinois" (abstract), *Illinois Acad. Sci. Trans.*, Vol. IX (1917), p. 210. W. C. Alden, "Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Survey Prof. Paper 106*, (1918), pp. 71–99. G. H. Cady, "Geology and Mineral Resources of the Hennepin and La Salle Quadrangles," *Illinois State Geol. Survey Bull. 37*, 1919. W. H. Twenhofel and F. T. Thwaites, "The Paleozoic Section of the Tomah and Sparta Quadrangles, Wisconsin," *Jour. Geol.*, Vol. XXVII (1919), pp. 614–33. E. O. Ulrich "Major Causes of Land and Sea Oscillations," *Washington Acad. Sci. Jour.*, Vol. X (1920), pp. 72, 77; *Smithsonian Report for 1920*, (1922), pp. 321–38.

Reference may also be made to the folios of the *Geologic Atlas of the United States*, Nos. 81, 140, 145, 200, and 201, and to publications dealing with Minnesota, Iowa, and northern Michigan; especially W. H. Norton *et al.*, "Underground Water Resources of Iowa," *U.S. Geol. Survey Water-Supply Paper 293*, 1912, and *Iowa Geol. Survey*, Vol. XXI, 1911; C. W. Hall *et al.*, "Geology and Underground Water of Southeastern Minnesota," *U.S. Geol. Survey Water-Supply Paper 256*, 1912; R. A. Smith, "Results of Deep Borings," *Michigan Geol. and Biol. Survey Pub. 24*, (1916), pp. 214–18, 238–39. A manuscript report on the Sparta and Tomah quadrangles, Wisconsin. is in the hands of the U.S. Survey, and Dr. Ulrich is preparing a report on the stratigraphy of Wisconsin.

THE PALEOZOIC SECTION (FIGS. 1 AND 2)

General.—The Paleozoic rocks of southern Wisconsin and northern Illinois comprise sediments of Cambrian, Ozarkian, Canadian, Ordovician, Silurian, and Devonian age. The Cambrian rocks are dominantly sandstones; higher in the column dolomite is more conspicuous. All the formations outcrop in Wisconsin, but in Illinois no Cambrian rocks appear at the surface. The tracing of individual formations from the outcrop to beneath cover has been done mainly by following certain markers or key-beds of well-defined lithologic character, rather than by counting down from the surface. For this purpose it was found desirable to construct sections where one horizon is drawn as a straight line, thus eliminating the confusing effect of structure. The sections herewith presented also show the sea level elevations of the wells. In the discussion of the several formations brief notes are given on their distribution and topographic expression. The data presented herewith are of a purely lithologic nature, the intention being to define the formations in such a manner that they can be distinguished by those not familiar with fossils and in wells where the finding of fossils is extremely uncommon.

Comparatively few of the Wisconsin well records based on samples have been published;[1] in Illinois the reverse is true.[2] The present paper does not aim to present the many well records in detail, but only the general results on which the correlations of the deeply buried strata are based.

DEVONIAN SYSTEM

Milwaukee Formation

Distribution.—The Milwaukee formation of Devonian age is known only near Milwaukee, Wisconsin, and in a few small adjacent areas. On account of the drift cover it shows no surface expression.

Character.—The Milwaukee formation is mainly dark gray dolomitic shale; there are some layers of gray shaly dolomite

[1] Samuel Weidman and A. R. Schultz, "The Underground and Surface Water Supplies of Wisconsin," *Wisconsin Geol. and Nat. Hist. Survey Bull. 35*, 1915.

[2] J. A. Udden, "Some Deep Borings in Illinois," *Illinois Geol. Survey Bull. 24*, 1914. C. B. Anderson, "The Artesian Waters of Northeastern Illinois," *Illinois Geol. Survey Bull. 34*, 1919.

which were formerly used for cement. The shale is called "soapstone," by local well drillers; it caves badly. The maximum known thickness is 168 feet at Milwaukee.

SILURIAN SYSTEM

Cayugan Series

General.—The Cayugan series is represented in Wisconsin by the very thin and discontinuous Waubakee dolomite which is found in spots along the Lake Michigan shore.

Niagaran Series
CLINTON AND LOCKPORT GROUPS

Distribution.—The Niagaran series of dolomites (Niagara formation of old reports) forms a conspicuous series of cuestas which extend south from the Door Peninsula in Wisconsin. South of Kewaunee County, Wisconsin, the minor escarpments which mark the different formations are covered by drift and south of Mayville, Wisconsin, the western edge of the belt is itself buried so deeply that the mapping of the Niagara area is based wholly on well records. In northwestern Illinois the Niagaran dolomites cap the higher hills, and a few scattered outliers are found in southwestern Wisconsin.

Character.—The Niagaran series of Wisconsin consists from the base up of the Mayville, Byron, Waukesha, Racine, and Guelph formations. The Waukesha of northeastern Wisconsin was called the Lower and Upper Coral beds in older literature. Ulrich places the Mayville in the Clinton group, and inasmuch as the Byron is poor in fossils, it is possible that the line of division might be drawn still higher. Ulrich has found a pre-Clinton dolomite (Burroughs dolomite) beneath the Niagaran in northwestern Illinois whose extent and character are but slightly known.

The Niagaran series is almost wholly light gray to pure white dolomite; locally pink, red, and less commonly, blue colors are met with in the lower portions. In southeastern Wisconsin and northeastern Illinois layers of blue, pink, and red calcareous shale are found near the base, notably at Milwaukee, Union Grove, and Racine, Wisconsin, and at Area, North Chicago, Maywood, and Elmhurst, Illinois. These basal rocks are probably older than the

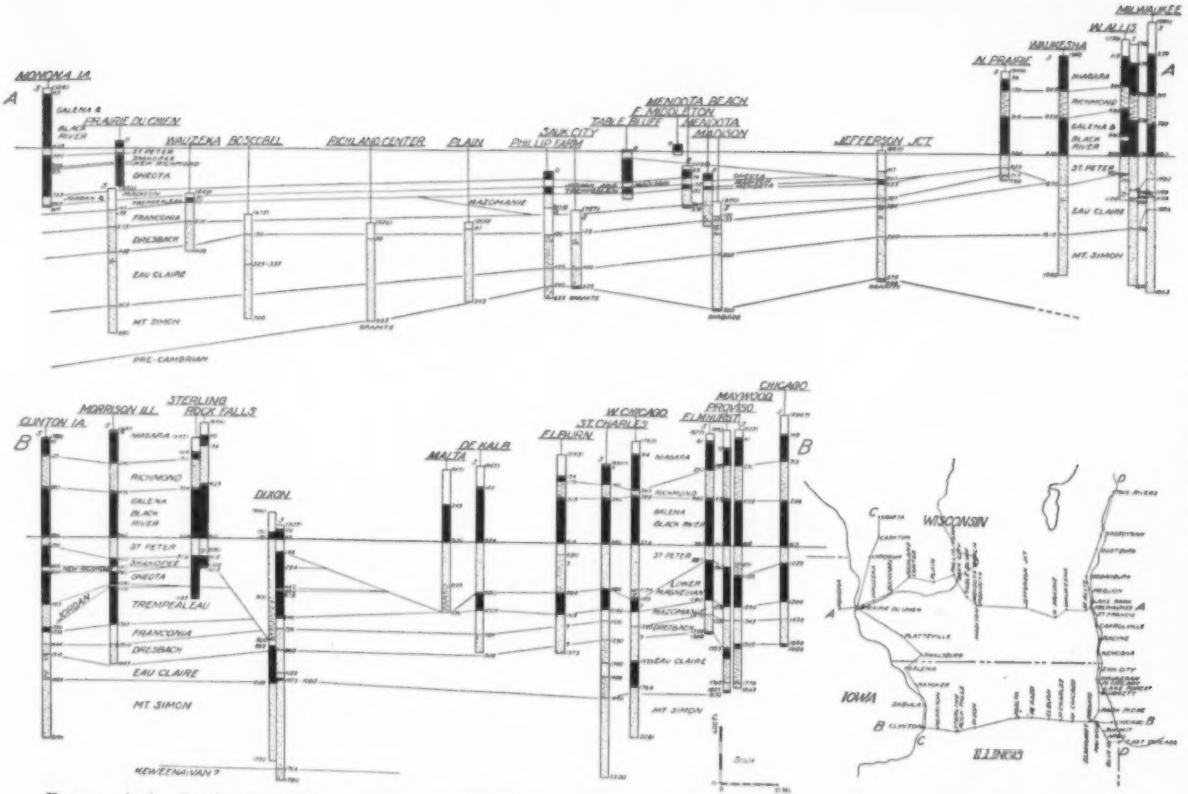

FIG. 1.—*A–A*. Section from Monona, Iowa, to Milwaukee, Wisconsin. *B–B*. Section from Clinton, Iowa, to Chicago, Illinois. Key map showing location of sections. These sections are drawn with the base of the Black River group as a horizontal line. Small figures at the right represent depths in feet; figures in parentheses represent sea level elevations of wells; *S* denotes record based on samples; *O* denotes outcrop. Drift is shown in white; limestone and dolomite in solid black; shale in broken lines; sandstone in dots; and sandy dolomite in black with white dots.

map showing location of sections. These sections are drawn with the base of the Black River group as a horizontal line. Small figures at the right represent depths in feet; figures in parentheses represent sea level elevations of wells; *S* denotes record based on samples; *O* denotes outcrop. Drift is shown in white; limestone and dolomite in solid black; shale in broken lines; sandstone in dots; and sandy dolomite in black with white dots.

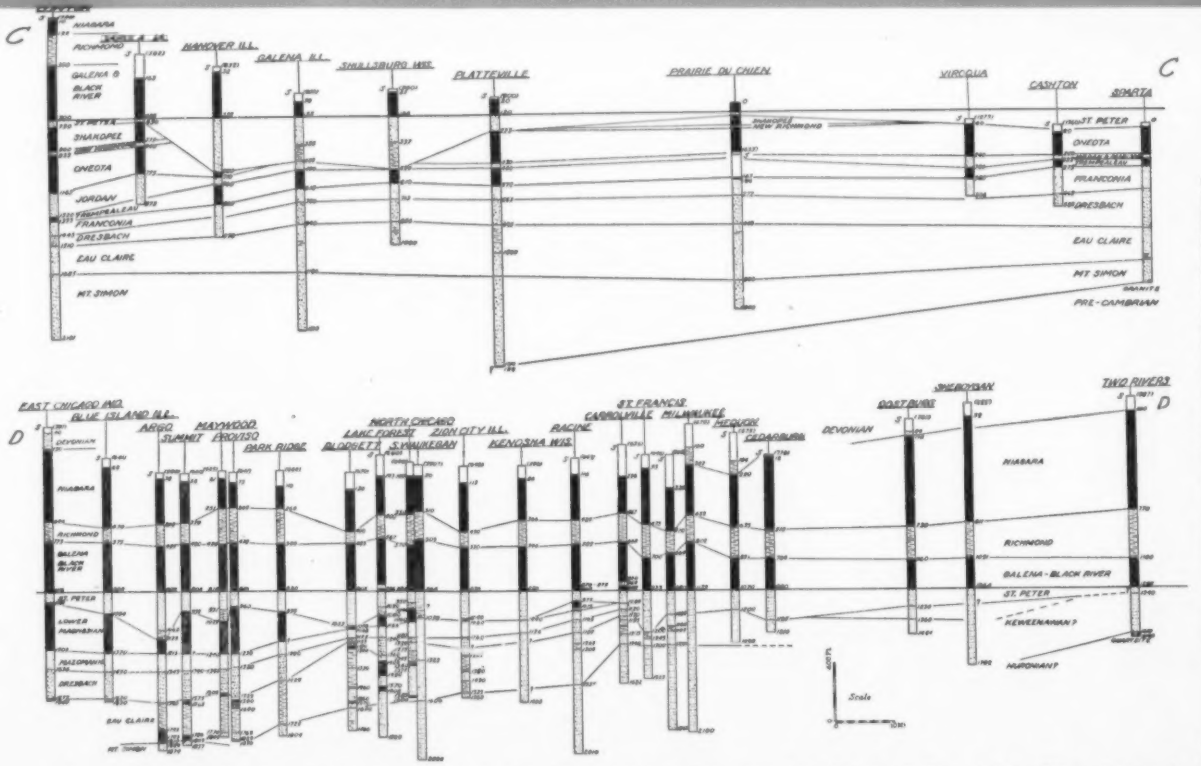

FIG. 2.—*C–C*. Section from Clinton, Iowa, to Sparta, Wisconsin. *D–D*. Section from East Chicago, Indiana, to Two Rivers, Wisconsin. These sections are drawn with the base of the Black River group as a horizontal line. Small figures at the right represent depths in feet; figures in parentheses represent sea level elevations of wells; *S* denotes record based on samples; *O* denotes outcrop. Drift is shown in white; limestone and dolomite in solid black; shale in broken lines; sandstone in dots; and sandy dolomite in black with white dots.

Mayville.[1] The bedding of the several formations varies from thin and regular in the Byron formation to massive in parts of the Waukesha and Racine formations. Indeed the separation of the formations in drill records is very difficult if no data on thickness of bedding are available. Chert of white and less commonly blue color is found in all the formations; it is most abundant in the basal Mayville and in the upper part of the Waukesha. The thickness of the whole Niagaran series varies from 300 to 670 feet increasing toward the northeast.

ORDOVICIAN SYSTEM[2]

MEDINAN SERIES

"CLINTON" OR NEDA FORMATION

General.—The "Clinton" or Neda formation occurs only in local lenses which outcrop in Dodge and Door counties, Wisconsin. These rise as mounds from the even surface of the Richmond. The Neda is found so rarely in deep wells that it requires no further discussion than to state that the deposits are oolitic hematite with subordinate red shale layers and shale pebbles.[3] The greatest known thickness is 55 feet at Manitowoc, Wisconsin.

RICHMOND GROUP

Distribution.—The Richmond group ("Cincinnati" or "Hudson River" formation of older reports) outcrops in a narrow belt along the Niagara escarpment in eastern Wisconsin and northeastern Illinois. In southwestern Wisconsin and northwestern Illinois there are many patches of Richmond beds, there called the Maquoketa shale.

Character.—The Richmond group in eastern Wisconsin consists mainly of dark blue calcareous shale, for the greater part very

[1] W. C. Alden, "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Survey Prof. Paper 106*, (1918), pp. 89–90. F. T. Thwaites, "Recent Discoveries of 'Clinton' Iron Ore in Eastern Wisconsin," *U.S. Geol. Survey Bull. 540*, (1913,) pp. 338–41.

[2] The Richmond group is placed in the Silurian by Ulrich, but all older writers and the majority of geologists at the present time place it in the Ordovician.

[3] The conclusions expressed by the writer in 1913 as to the feasibility of mining this ore under heavy cover need revision. There is now little question that the red beds near Kenosha are not iron ore, and that a fault occurs near Manitowoc; this would cause great difficulty with water at the latter locality.

soft, but in some layers of slate-like consistency. Interstratified with the shale at certain horizons are beds of gray and blue dolomite and magnesian limestone. In northeastern Wisconsin portions of the shale are brown-colored and, when heated, give off a strong oily odor. The correct interpretation of drill samples is hampered by the fact that some have been washed while others have not; the former give quite an erroneous impression of the character of the material.

In northeastern Wisconsin the following subdivisions of the Richmond group have been distinguished in wells: in ascending order (*a*) brown shale about 100 feet; (*b*) blue shale 58 to 105 feet; (*c*) brown shale, locally gray and slaty 5 to 62 feet; (*d*) blue shale 34 to 105 feet; (*e*) blue and gray dolomite interbedded with blue shale 35 to 70 feet; (*f*) blue shale 42 to 90 feet, and (*g*) gray, blue, and purple shaly dolomite with nodules of chert and gypsum 35 to 50 feet. Of the foregoing (*a*) is known only at Sturgeon Bay; (*e*), (*f*), (*g*), and possibly (*d*) are exposed at the surface; and (*c*) is quite irregular in distribution and thickness. The last is readily overlooked as the dried samples are hard to distinguish from the grayish blue shales above and below. The Niagaran dolomites bevel across the top of the group so that as one goes south along the shore of Lake Michigan, the younger series rests upon successively older and older members of the Richmond. Where the Mayville dolomite rests upon the dolomite member (*e*), the exact plane of contact is difficult to determine. Throughout this district the Richmond group varies from a thickness of about 200 feet near Milwaukee, to over 540 feet in southern Door County.

In northern Illinois the group is thinner and very variable, both in thickness and in lithological character. Calvin[1] describes a full section of the Maquoketa beds in Iowa as, ascending (*a*) Elgin shaly limestones (limestones, dolomites, and shaly limestones interstratified with blue calcareous shale) 70 feet; (*b*) Clermont shale (blue shale) 15 feet; (*c*) Fort Atkinson limestone (yellow cherty dolomite and limestone) 40 feet; (*d*) Brainard shales (blue shale with limestone beds at top and bottom) 120 feet. Savage[2]

[1] Samuel Calvin, "Geology of Winneshiek County," *Iowa Geol. Survey*, Vol. XVI (1906), pp. 94–109.

[2] T. E. Savage, "Geology of Jackson County," *Iowa Geol. Survey*, Vol. XVI (1906), pp. 597–609.

states that the distribution of these members is erratic and that those below the Brainard shales are missing in some counties. There also appears to be considerable irregularity at the top of the Maquoketa. Ulrich[1] divided the Richmond of Iowa into several formations: ascending (*a*) Dubuque dolomite, (*b*) Wykoff limestone, (*c*) Clermont shale, (*d*) Maquoketa shale, (*e*) Fort Atkinson limestone, (*f*) Brainard shale, and (*g*) unnamed dolomite. In later unpublished work the succession is given as (ascending) Dubuque dolomite, Elgin shale, Fort Atkinson limestone, and Brainard shales. Whatever may be the final disposition of these divisions as members or as separate formations, it is clear that the irregularity of sequence in the Richmond group is due to the disappearance of certain lithologic units, both at the base and the top of the group. Most well records in northern Illinois show only blue calcareous shale; some disclose limestone, or dolomite layers, at either the top or the bottom of the group.

Mohawkian Series
Trenton and Black River groups

Distribution.—The Trenton group of Wisconsin is called the Galena formation, and the underlying Black River group was incorrectly termed Trenton in older literature. The revision of the formation names within these groups has not yet been entirely completed for Wisconsin, and since the two groups constitute a lithologic unit of limestones and dolomites a detailed discussion of this subject would be of little value in this paper.

The Trenton and Black River groups (Galena-Trenton of older reports) cap a broad cuesta in eastern and southern Wisconsin, whose escarpment is well marked from Oconto southwest to Green Lake, and from Cross Plains west along the north side of Military Ridge to Mississippi River. The groups constitute the surface rock of most of the southern Driftless Area and of much of northwestern Illinois.

Character.—In southwestern Wisconsin and northwestern Illinois the Black River group consists in ascending order of the Platteville calcitic limestone and the Decorah shale and shaly limestone.

[1] E. O. Ulrich, "Revision of the Paleozoic Systems," *Geol. Soc. Amer. Bull.*, Vol. XXII (1911), pp. 281–680.

Passing to the east, dolomite becomes more and more abundant until near Beloit, Wisconsin, the entire group consists of buff and blue dolomite; Sardeson proposed the name Beloit for the eastern equivalent of the Decorah and Platteville formations. The Galena formation is everywhere a dolomite; it is rather coarse grained, gray at depth, and weathers to a yellow sandy consistency near the surface. At its base in southwestern Wisconsin Ulrich finds the Prosser formation of Minnesota.

In northeastern Wisconsin less is known of either group. The Galena is certainly present as a gray dolomite with some bluish gray shaly partings. On lithologic grounds the entire thickness of

TABLE I

PARTIAL LOG OF WATERWORKS WELL, CEDARBURG, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Dolomite, gray	110	815
Dolomite, mixed gray and light blue	5	820
Dolomite, gray	10	830
Dolomite, mixed light blue and gray	35	865
Dolomite, gray	25	890
Dolomite, bluish gray and gray	15	905
Dolomite, gray	10	915
Dolomite, gray, sandy	5	920
Total thickness	215	.....

dolomites of that district can be divided into two divisions; of these the upper is almost wholly gray and the lower is blue, mottled blue and gray, and gray only in a few thin beds. Partings of blue dolomitic shale are much more common throughout the lower division. The well log shown in Table I is typical of this formation in eastern Wisconsin.

Too little is known of the outcrops in this region to warrant the writer in attempting to correlate the succession found in wells with the section to the southwest. Chert is conspicuous on all weathered outcrops of both the Galena and Beloit formations but is seldom met with in drill cuttings from eastern Wisconsin and northeastern Illinois. The chert is gray or white at depth, although weathered specimens assume a yellow color. In much of eastern

Wisconsin fresh rock is found immediately below the drift, so that the characteristic weathered phases of the west are wanting. The base of the Black River is sandy in many localities, and along a belt which runs south from Milwaukee parallel with the Lake Michigan shore, there is a distinct bed of sandstone near the bottom of the group; this is known to well drillers as the "Trenton Stray Sand." It has a maximum known thickness of about 30 feet and consists of rather coarse-grained gray calcareous sandstone. This rock differs from the St. Peter in greater size of grain, lack of chert fragments, and in its dolomite cement which is locally sufficient to cause the rock to break in thin chips under the drill. The "stray sand" is confined, so far as known, to an area where the thickness of the Trenton and Black River groups is over 300 feet, although it is not present everywhere that the dolomites reach that thickness. It is probable that locally it lies directly upon the St. Peter, but where it can be distinguished with certainty, there are a few feet of more or less sandy dolomite between the two sandstones. There are some evidences that the "stray sand" is present elsewhere in Wisconsin. The thickness of the entire Trenton and Black River groups varies from 179 to 450 feet.

Big Buffalo Series
St. Peter formation

Distribution.—The St. Peter formation outcrops in the Galena–Black River escarpment, along valleys which cut the back slope of the cuesta, and in small inliers as far south as La Salle, Illinois. Being a soft formation it forms either steep slopes with occasional cliffs and crags, or low broken country with many small knolls. The extent in Illinois is greater than indicated on existing geological maps, for well records show it to lie immediately below the drift of valleys as far south as Rockford.

Character.—The St. Peter is dominantly a light gray or yellowish gray, fine to medium grained, more or less dolomitic sandstone; below the sandstone are beds of purplish red and green shale interstratified with layers of white disintegrated chert, and conglomerate with chert and limestone pebbles in a matrix of fine to coarse sand. These basal beds cave very badly in wells and must generally be cased off. At Shullsburg, Wisconsin; Galena, Illinois,

and elsewhere they are a very difficult horizon to penetrate with the drill. The caved material mixes with cuttings from lower horizons making some records very hard to interpret. The record is typical of the St. Peter where the basal beds are thick (Table II). The thickness of the St. Peter sandstone and underlying shales and conglomerate is known to reach at least 325 feet and may possibly exceed 600 feet in Illinois; in Wisconsin the maximum thus far

TABLE II

PARTIAL LOG OF WATERWORKS WELL, SHULLSBURG, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Sandstone, coarse, gray, very calcareous; pyrite	5	193
Sandstone, medium to fine, light gray	77	270
Sandstone, medium to coarse, light gray	20	290
Sandstone, medium, light yellowish gray	35	325
Sandstone, medium, light pink	7	332
Sandstone, medium, light yellowish gray	15	347
Sandstone, medium to coarse, reddish gray; some red shale at top	18	365
Sandstone, medium, light yellowish gray	30	395
Sandstone, coarse, red; shale, red	2	397
Shale, dark red with greenish gray spots and pebbles of white chert	38	435
Conglomerate: pebbles white chert, matrix red shale	18	453
Shale, red with greenish gray spots and a few pebbles of white chert	5	458
Conglomerate like above	4	462
Shale, red and green mixed, pebbles of white chert and some sand	20	482
Sandstone, fine, gray, very calcareous; chert and red shale, caves badly, probably conglomerate	20	502
Sandstone, fine, gray, pink and green mixed; and red shale, caves badly, probably conglomerate	18	520
Total thickness	332	.....

recorded in 332 feet, at Shullsburg. Its average thickness is very much less.

Sub-St. Peter unconformity.—Study of well records leaves no doubt that there is an unconformity of great magnitude at the base of the St. Peter. The shales at this horizon are virtually all non-calcareous and appear to be more or less deoxidized residium from the underlying dolomites. The chert beds and conglomerates represent assortment of residual deposits by water. The relief of the surface of the underlying dolomites is over 300 feet; places with no St. Peter sandstone occur within a few miles of localities

where there is no Lower Magnesian.[1] An example of this phenomenon occurs between Green Bay and De Pere, Wisconsin. Over an area of several thousand square miles in eastern Wisconsin and in portions of northern Illinois, the St. Peter rests upon the Cambrian; formations ranging from Jordan to Eau Claire have been distinguished at different places as underlying the St. Peter. The bottom of the St. Peter is best studied from well records, since the softness of the rocks causes this horizon to be concealed quite generally at the surface. At some exposures the beds of the underlying dolomite dip with the irregularity of the bottom of the sandstone; the writer is not prepared to state the significance of this phenomenon. Where the St. Peter rests upon the Cambrian sandstones, it is at places almost impossible to make out the exact plane of contact; such is the case near Milwaukee.

CANADIAN AND OZARKIAN SYSTEMS[2]

LOWER MAGNESIAN GROUP (PRAIRIE DU CHIEN FORMATION)

Distribution.—The Lower Magnesian group has been termed the Prairie du Chien formation in some reports; however, Ulrich urges that the old name be retained for the present. He divides the group in ascending order into the Oneota dolomite, the New Richmond sandstone, and the Shakopee dolomite; of these he places the first in his Ozarkian system and the others in his Canadian system. The group caps a broad, well defined cuesta whose U-shaped escarpment surrounds the central plain of Wisconsin. In Illinois only a few small inliers of the Shakopee are associated with the areas of exposed St. Peter sandstone.

Character.—The exact discrimination of the several formations of the Lower Magnesian group has thus far been made only in the outcrops of the western part of Wisconsin. These formations can be followed in well records for some distance into Iowa and Illinois. The two dolomites are rather similar in character, both are gray and carry gray, yellow, and pink chert, some of which is oolitic. The presence of oolitic chert is a certain marker of the Lower

[1] According to Ulrich all this is good evidence tending to establish this unconformity as marking the base of the Ordovician in the Mississippi Valley.

[2] These systems have been proposed by Ulrich and have not as yet been generally recognized; others place most of the formations concerned in the Ordovician.

Magnesian group since it has never been discovered in any of the adjacent dolomite formations. In places where the underlying or overlying sandstones are absent this criterion is almost indispensable. In northeastern Wisconsin there are pink shaly layers within the Lower Magnesian which can readily be confused with the

TABLE III

PARTIAL LOG OF WELL OF PESHTIGO PULP AND PAPER COMPANY, PESHTIGO, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Dolomite, mixed gray and bluish gray	5	125
Dolomite, gray; oolitic chert, gray; specks of blue and green shale; caves	20	145
Dolomite, gray; shale, green; sandstone, gray	15	160
Dolomite, gray in part with floating sand grains; shale, blue; sandstone, fine, gray	15	175
Dolomite, gray; shale, blue; chert, pink	10	185
Sandstone, coarse to medium, light gray, calcareous	15	200
Sandstone, like above with layers of dark and light gray dolomite	5	205
Dolomite, dark and light gray, floating sand grains; layers of gray calcareous sandstone	5	210
Dolomite, dark and light gray layers	42	252
Dolomite, light gray; chert, oolitic, light gray	3	255
Dolomite, light gray; some sandstone, purplish, red, calcareous	5	260
Dolomite, banded purplish red, gray, and green, shaly, sandy	5	265
Sandstone, coarse to medium, light pink, very calcareous	2	267
Dolomite, gray, green, and pink with layers of sandstone like above	8	275
Dolomite, light gray	10	285
Dolomite, gray with layers of sandstone and some oolitic chert	4	289
Dolomite, gray with much gray chert	4	293
Dolomite, gray with some chert	22	315
Dolomite, coarsely crystalline, gray	7	322
Dolomite, white and gray, chert, gray, both oolitic and dense	4	326
Dolomite, gray	41	367
Total thickness	247	.....

underlying red beds of the Trempealeau. The writer has placed the bottom of the group at the lowest cherty gray dolomite.

Sandstone beds occur at several levels in the Lower Magnesian group and, except in northwestern Illinois and southwestern Wisconsin, have not been correlated with the formations described above. For the most part the sandstones are relatively coarse grained, light gray or white, and locally contain thin layers of dolomite and less frequently chert pebbles. A white sandstone

with abundant specks of green shale occurs near the base of the Oneota in western Wisconsin. In northeastern Wisconsin there are several "stray sands" some of which have doubtless been mistaken by well drillers for St. Peter. These sandstones are not good markers; closely spaced records in the Fox River Valley show that they pass horizontally within relatively short distances into floating sand grains in a dolomite matrix. The well record in Table III shows the character of the Lower Magnesian group in far northeastern Wisconsin. Not enough work has been done on the outcrops in this region to permit of correlating any of these beds with the western section.

The maximum known thickness of the Lower Magnesian group is over 700 feet in western Illinois; to the northeast it is much thinner, in many places less than 100 feet. Throughout several counties in eastern Wisconsin the dolomite is absent so far as known from well records; within this district its horizon is represented in some places by a thin layer of chert and non-calcareous clay, residium of the cherty dolomites, but near Milwaukee no trace of the Lower Magnesian has been found.

CAMBRIAN SYSTEM[1]

Madison Formation

Distribution.—The type locality of the Madison formation is the quarries just west of Madison. The formation, which lies immediately beneath the Oneota, has been traced in outcrops from that locality about 25 miles to the west. A few outcrops occur east of Madison, and it is also known in a well record at Sun Prairie, Wisconsin. Beds of somewhat similar character in the western part of Wisconsin are believed by Ulrich to represent the Madison.

Character.—The Madison of the original locality is a fine grained, buff, calcareous sandstone at the top, which passes below to a pure white medium grained sandstone much like the Jordan. In well samples it can only be distinguished from the Jordan, which underlies it throughout western Wisconsin, by its yellow color and dolomitic cement. The maximum thickness is about 50 feet.

[1] The Madison formation is regarded as the top of the Cambrian by most geologists; Ulrich places the top of that system at a lower horizon.

Mendota Formation

Distribution.—The Mendota dolomite as defined by Ulrich outcrops only in two small areas, one near Madison and the other near Baraboo, Wisconsin, where it caps small hills and terraces. It has not been definitely followed underground for more than a score of miles to the east of Madison, but may extend much farther.

Character.—The Mendota formation is a gray dolomite with purple and greenish gray blotches; glauconite is sparingly present and chert is nowhere found. In southeastern Wisconsin and northeastern Illinois there is a considerable thickness of chert-free, purple-spotted dolomite beneath the typical Oneota with its oolitic chert and green shale specks. If, as is known to be the case with the Jordan, the Madison loses its lithologic identity when followed down the dip from its outcrop, this rock may be in part at least of Mendota age.[1] The maximum proved thickness of the Mendota is about 20 feet, but if some of the non-cherty dolomite of Illinois is of the same age, the thickness may be several times as much.

[1] The stratigraphic position of the Mendota has caused more difficulty than any other problem within the area under discussion. Near Madison it is overlain by the Madison sandstone. Two or three feet of dolomite below the massive layers of the Mendota are regarded by Ulrich as the equivalent of the St. Lawrence or Black Earth dolomite member of the Trempealeau formation of western Wisconsin but contain no fossils. Under these layers is the Mazomanie sandstone with the same character, thickness, and with its top at exactly the same distance below the base of the Oneota as in the western section. At the west end of Lake Mendota we have in ascending order (*a*) Mazomanie sandstone, (*b*) red shale and glauconitic sandstone, (*c*) St. Lawrence or Black Earth dolomite member, (*d*) Lodi sandy dolomite member of Trempealeau formation, (*e*) Jordan sandstone, (*f*) Madison sandstone, and (*g*) Oneota dolomite. Two miles east we have a section so similar in lithologic character that were it not for the fossils described by Ulrich it would never have occurred to anyone to question its equivalence. The only difference is that (*d*) is thin or locally absent. According to Ulrich the testimony of the fossils places the Mendota dolomite of the south and east shores of Lake Mendota in his proposed Ozarkian system, in other words as younger than the Jordan sandstone. The fossils of the St. Lawrence or Black Earth member of the Trempealeau formation are strikingly similar to those of the Mendota although they show certain differences. The paleontological evidence is, therefore, at the present date entirely unsupported by stratigraphic data in this district. The exposures of Mendota dolomite near Baraboo do not show the same adjoining formations as at Madison; indeed the stratigraphic section close to the quartzite islands is in many respects quite different from elsewhere. It is therefore a question whether or not the Mendota of Baraboo is the same as the original Mendota dolomite at Madison; the correlation rests solely upon fossils. The entire question is fortunately of little importance in the study of well records since the Mendota is of very limited occurrence.

Devils Lake Formation

Distribution.—The Devils Lake formation is known only in a few exposures near the quartzite ranges at Baraboo, Wisconsin. It has never been located in a complete normal section away from the old beaches; indeed it is not positively known if all of the supposed occurrences are of the same age.

Character.—The Devils Lake formation consists of gray and yellow, more or less glauconitic sandstone and of quartzite pebble conglomerate. In the best known exposures, southwest of Baraboo, it is underlain by glauconitic sandstone and purple spotted dolomite unlike anything known in the normal section outside the quartzite ranges; at other places the formation has been found resting on the Jordan, and possibly on other formations. It is overlain in some places by the Mendota dolomite, and in others apparently by the Oneota dolomite. The formation in question is of no importance in the study of well records on account of its limited distribution; it is barely possible that some of the strata in southeastern Wisconsin here ascribed to the Mazomanie formation are Devils Lake. The thickness of the Devils Lake is not definitely known but may reach a maximum of over 100 feet.

CAMBRIAN SYSTEM[1]

Upper Cambrian Series (St. Croix Group)

JORDAN FORMATION

Distribution.—The Jordan sandstone outcrops in a narrow belt along the Lower Magnesian escarpment and in the sides of valleys within the cuesta as far east as near Cross Plains, Wisconsin; east of that point it has not been definitely distinguished. On the Mississippi it passes beneath the surface near Prairie du Chien, Wisconsin.

Character.—The Jordan sandstone is noted for its pure white color although in places some outcrops are yellow. The grain is fine to medium; calcite or dolomite concretions are abundant at the surface. Followed down the dip into northwestern Illinois the formation loses its identity as a lithologic unit and grades into sandy dolomite; no Jordan sandstone has been distinguished in

[1] As defined by Ulrich.

most of northeastern Wisconsin. The maximum thickness of the Jordan is about 75 feet; its lower limit is determined by the finer grain and more dolomitic character of the underlying Trempealeau.

TREMPEALEAU FORMATION

Distribution.—The Trempealeau formation has been called the St. Lawrence formation, and in older literature was correlated with the Mendota of the Madison region. The definition of this formation has varied from merely the thin "Black Earth" or original St. Lawrence dolomite bed, to all the strata between the base of the Jordan and the top of the Dresbach. In view of this conflict Ulrich has recently proposed a change in name.[1]

The Trempealeau formation caps narrow terraces just beneath the steep slopes of the Jordan outcrop. It is known throughout western Wisconsin and northwestern Illinois, but has not been definitely distinguished southeast of a northeast-southwest line through Madison.

Character.—The Trempealeau formation is divided by Ulrich into the following members from base up: (*a*) sandy dolomitic shales of local distribution, (*b*) St. Lawrence or Black Earth dolomite, a rock almost exactly like the Mendota, (*c*) Lodi yellow and purple sandy thin bedded dolomite, locally called "shale," and (*d*) Norwalk fine grained dolomitic sandstone. Of these the last is most conspicuous in western Wisconsin; along the Wisconsin River the Lodi "shales" predominate and farther south under cover there is less sand and (*b*) seems to make up the bulk of the formation. The yellow color does not persist in depth but is replaced by gray; this is not true of the purple tints. The base of the formation is marked by a greensand conglomerate; glauconite is only sparingly present at higher horizons.

The red and purple dolomites, for the most part quite sandy, that underlie the cherty gray Oneota in northeastern Wisconsin have been correlated by the writer with the Trempealeau formation; they are in few places separated from the younger dolomite by a sandstone. In western Wisconsin, however, the Trempealeau is overlain by the Jordan sandstone.

[1] At the date of writing the name Trempealeau has not been approved by the Board of Geologic Names of the U.S. Geological Survey.

The thickness of the Trempealeau formation is at a minimum of 35 feet in northeastern Wisconsin; in the southwestern district it exceeds 100 feet. The record shown in Table IV is typical of northeastern Wisconsin.

TABLE IV

PARTIAL LOG OF STATE REFORMATORY WELL, GREEN BAY, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Dolomite, gray, sandy; layers of sandstone, fine, pink, hard, calcareous	15	470
Sandstone, fine to very fine, gray, pink, very calcareous, hard	15	485
Sandstone like above but in part red and glauconitic	5	490
Total thickness	35	.....

MAZOMANIE FORMATION

Distribution.—The Mazomanie sandstone is known from far northeastern Wisconsin to near Spring Green, Wisconsin. It is a rather firm rock and forms conspicuous crags among which may be mentioned the Natural Bridge, west of Prairie du Sac. A line drawn from Spring Green east of north through central Adams County separates the Mazomanie from the Franconia. The Mazomanie thins out to the west and overlaps the older Franconia for distances of 10 to 20 miles. Good examples of Mazomanie overlying Franconia can be found near Reedsburg and Friendship.

Character.—The Mazomanie consists of fine to medium grained gray to dark red sandstone, irregularly cemented by dolomite; locally there are beds of red, green, and gray calcareous shale. At depth some layers are so well cemented that they break into chips under the drill and are hence reported as limestone in drillers' logs, or described as sandy dolomite by some geologists who have examined samples. At Markesan and Green Lake, Wisconsin, the base of the Mazomanie consists of gray dolomite with purple spots, very similar to the St. Lawrence member of the Trempealeau. The red colors are of local distribution; they are mainly found in northeastern Illinois. The entire formation contains more or less glauconite and that mineral is most abundant near the top. This fact makes the Mazomanie a valuable marker in the geological column. The record is typical of the Mazomanie of eastern

Wisconsin and northeastern Illinois (Table V). In northern Illinois it was formerly correlated with the Madison and Mendota of

TABLE V

PARTIAL LOG OF CITY WELL NO. 4, KAUKAUNA, WISCONSIN

	Thicknes (Feet)	Depth (Feet)
Sandstone, very fine, pink and brownish red, very calcareous, glauconitic; seams of green shale	35	415
Sandstone, fine, mixed greenish gray and red, calcareous, glauconitic	15	430
Sandstone, coarse to fine, pinkish gray, hard, very calcareous	5	435
Sandstone, coarse to medium, white	20	455
Sandstone, medium to coarse, white, part pink and gray, calcareous	5	460
Sandstone, medium to coarse, white	25	485
Sandstone, medium to fine, white, hard, calcareous	10	495
Sandstone, very fine, gray, calcareous; shale, gray	5	500
Shale, gray, calcareous	5	505
Sandstone, fine, gray, calcareous; shale, gray, calcareous	5	510
Total thickness	130	.....

Wisconsin, but bears no resemblance to those formations.[1] The thickness averages close to 100 feet with a maximum of 165 feet.

FRANCONIA FORMATION

Distribution.—The Franconia sandstone caps a wide cuesta in western Wisconsin which extends southeast from St. Croix Falls to near Baraboo. It also forms a bench along the valley sides within the Lower Magnesian cuesta. The surface of the formation is divided into several minor terraces each corresponding to some difference in relative resistance to weathering.

Character.—The Franconia sandstone is fine grained, gray to green in color, and for the most part somewhat calcareous. However, the lithologic character of the formation varies considerably in different parts of the state, and there are rapid changes in the character of the formation. For instance the yellowish sandstone of the Sparta district is represented near Viroqua at the same stratigraphic level by dark green clay shale. The greater part of the Franconia is highly glauconitic, especially near the bottom and

[1] C. B. Anderson, "The Artesian Waters of Northeastern Illinois," *Illinois State Geol. Survey Bull. 34* (1919), pp. 84, 107.

top. Near the base, particularly in the southwestern quarter of the state, is about 15 feet of micaceous sandy shale; this horizon is very important in wells since under ridges the water is held above it causing a spring line around the sides of bluffs. If wells go through the shale, the water level drops very markedly. Below the shale are a few feet of hard calcareous coarse-grained sandstone, the Ironton member. The thickness of the Franconia varies from 90 to 175 feet.

DRESBACH FORMATION

Distribution.—The Dresbach sandstone forms the cliffs of the Franconia escarpment in western Wisconsin. It is prominent in the numerous fantastic towers and buttes of the central part of the state. In the valleys within the Lower Magnesian cuesta, it outcrops in cliffs along the streams as far south as near Lone Rock on Wisconsin River. The white cliffs west of Prairie du Sac are Dresbach.

Character.—The Dresbach consists of medium-grained pure white sandstone with some yellow layers. The cement is mainly silica and varies greatly in amount; locally the formation is quartzitic. The upper and lower contacts are difficult to make out in some well sections. The writer has excluded from the formation all fine-grained, calcareous, or glauconitic sandstones. In central and northeastern Wisconsin the base cannot be determined, since the only change is in thickness of bedding. Not counting this district, the thickness varies from 40 feet at Union Grove, Wisconsin, to 180 feet at Chicago. In consequence of the high porosity and great purity of the formation it yields excellent water.

The Dresbach sandstone of Illinois was formerly correlated with the Jordan,[1] but the writer is convinced that this was an error because of the similarity of the succession of formations in deep wells to that found in outcrops near Sauk City, Wisconsin, and by the fact that the underlying formations are totally unlike any known Trempealeau, Franconia, or Mazomanie. The white sandstone formation has been followed through in well sections

[1] C. B. Anderson, "The Artesian Waters of Northeastern Illinois," *Illinois State Geol. Survey Bull. 34*, (1919), pp. 84, 107, Pl. II.

across Illinois to the outcrops near Prairie du Chien and La Crosse, Wisconsin, as well as directly northwest to Sauk City, Wisconsin.

EAU CLAIRE FORMATION

Distribution.—The Eau Claire formation underlies a large part of the lowlands of central Wisconsin. It forms flat-topped terraces and rolling country of low relief, only occasionally making a steep escarpment like that of the Dresbach. The formation outcrops along Mississippi River as far south as La Crosse. The thin bedded, cross bedded rock in the Dells of the Wisconsin is believed to belong to the Eau Claire.

Character.—The Eau Claire formation consists of sandstone and shale whose relative proportions differ greatly according to locality. In northeastern Wisconsin both outcrops and well records show clearly that the entire formation is sandstone of medium to fine grain, indistinguishable except by its thin bedding from either the overlying or underlying formations. In western Wisconsin, where the Eau Claire was first studied, the upper and lower parts are filled with thin seams and small lenses of greenish or bluish gray shale and most of the sandstone is very fine grained. There is some glauconite but not so much as in the younger Franconia; linguloid shells are locally prominent. The formation with increasing percentage of shale has been followed south in well records into northern Illinois. The section in that region bears so close a resemblance to that near Chicago that there can be no reasonable doubt that the shales below the white sandstone (Dresbach) of the east part of Illinois are the Eau Claire. A three-part subdivision is persistent; west of Chicago a fine-grained calcareous sandstone separates two members of gray and red calcareous shale or marl with some dolomite beds. On the whole, however, the Eau Claire is marked by extreme variability in character. Scarcely any two wells record exactly the same succession in detail; beds of gray marl, red marl, fine, medium, or rarely coarse-grained sandstone of pink, gray, or white colors alternate with very calcareous sandstones and in places pure dolomites, but in almost every case some vestige of the tripartate subdivision can be made out. Dolomite beds are commonest near the bottom and the top of the formation.

The records as shown in Tables VI and VII illustrate the variable character of the Eau Claire of the southeastern part of the area

TABLE VI

PARTIAL LOG OF ABBOTT LABORATORIES WELL, NORTH CHICAGO, ILLINOIS

	Thickness (Feet)	Depth (Feet)
Sandstone, very fine, gray, shaly, calcareous, slightly glauconitic; pyrite	30	1,250
Sandstone, fine to very fine, gray, calcareous	10	1,260
Shale, red, calcareous	15	1,275
Shale, gray, calcareous	35	1,310
Shale, mixed red and gray, calcareous	20	1,330
Shale, gray, calcareous	15	1,345
Sandstone, very fine, gray, calcareous	15	1,360
Dolomite, light gray	15	1,375
Sandstone, fine, gray, calcareous	125	1,500
Sandstone, very fine, gray, calcareous	35	1,535
Sandstone, very fine, gray, hard, very calcareous	25	1,560
Sandstone, exceedingly fine, gray, calcareous	10	1,570
Sandstone, fine, gray, calcareous	15	1,585
Dolomite, gray to bottom of well	15	1,600
Total thickness over	380	.....

TABLE VII

PARTIAL LOG OF WELL AT SOUTHERN WISCONSIN HOME FOR THE FEEBLE-MINDED AND THE EPILEPTIC, UNION GROVE, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Sandstone, very fine, brownish gray, calcareous	75	1,040
Sandstone, very fine, dark red, very calcareous, glauconitic	30	1,070
Shale, red with some gray beds, very calcareous	50	1,120
Sandstone, medium to very fine, pink, calcareous	20	1,140
Sandstone, medium to fine, light pinkish gray, calcareous	25	1,165
Sandstone, fine, gray, calcareous, coarser toward base	30	1,195
Sandstone, fine, gray, calcareous	30	1,225
Sandstone, medium to fine, dark gray, calcareous	15	1,240
Sandstone, fine, yellowish gray, calcareous	10	1,250
Sandstone, fine, gray, slightly calcareous	15	1,265
Sandstone, fine, white	10	1,275
Sandstone, fine to shaly, red, very calcareous	5	1,280
Sandstone, exceedingly fine, yellowish gray, calcareous	5	1,285
Shale, red, calcareous	5	1,290
Sandstone, medium to fine, pinkish gray, calcareous	45	1,335
Sandstone, medium to fine, gray, calcareous	20	1,355
Sandstone, very fine, pinkish gray, calcareous	5	1,360
Total thickness	395	.....

under discussion; it is here much more shaly and dolomitic than nearer the outcrop.

In the region around Milwaukee the greatest difficulty was experienced in correlating the "red marl zone" as it is known to well drillers. The gray shales are almost entirely lacking in that district and the red layers are so erratic in both vertical and horizontal distribution that at first the problem seemed hopeless. The red marl at Milwaukee was formerly believed to be part of the Lower Magnesian.[1] However, by means of sections parallel to the lake shore it was determined that the red marls pass below the Dresbach sandstone of Illinois, and grade laterally into the gray and red marls of the Chicago district. This conclusion was verified by fossils which were shot out of a well at Waukesha and determined by Dr. Ulrich.

The thickness of the Eau Claire, as it can be distinguished in well records, varies from 70 feet at Rockford, Illinois, to 410 feet at St. Charles, Illinois; the average is not far from 350 feet.

MT. SIMON FORMATION

Distribution.—Outcrops of the Mt. Simon sandstone have thus far been studied only near Eau Claire, Wisconsin, its type locality. At that place it forms an escarpment which is capped by Eau Claire shaly sandstone. The Mt. Simon must be the basal member of the Cambrian over a wide area of drift-covered country in central Wisconsin.

Character.—The upper limit of the Mt. Simon sandstone is difficult to determine on account of the variable character of the overlying Eau Claire. In central Wisconsin the formation is mainly coarse to medium grained, gray or yellow sandstone with a few layers of green, blue, and red shale. Farther south less of the formation is coarse grained; locally there are pink layers, the color being deepest in the finer-grained sands. The record (Table VIII) is a fair example of the Mt. Simon rather close to the outcrop where there are more beds of coarse grain than farther south. The greatest recorded thickness is 778 feet at Platteville, Wisconsin.

[1] W. C. Alden, "Geol. Atlas of U.S.," *Milwaukee Folio No. 140*, (1906), p. 1; "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Survey Prof. Paper 106*, (1918), pp. 78–82. Samuel Weidman and A. R. Schultz, "The Underground and Surface Water Supplies of Wisconsin," *Wisconsin Geol. and Nat. Hist. Survey Bull. 35*, (1915), p. 457.

PRE-CAMBRIAN SYSTEMS

Base of the Paleozoic rocks.—The Paleozoic series rests upon a rather irregular basement of pre-Cambrian igneous and metamorphic rocks. Older attempts[1] to map this surface have not shown nearly as many buried monadnocks as are now known. For the most part these are composed of Huronian quartzite, not unlike

TABLE VIII

PARTIAL LOG OF CITY WELL NO. 11, MADISON, WISCONSIN

	Thickness (Feet)	Depth (Feet)
Sandstone, medium to fine, white	25	390
Sandstone, medium to fine, white; some beds hard, calcareous, pink	60	450
Sandstone, medium to fine, light gray	25	475
Sandstone, coarse to medium, light gray	45	520
Sandstone like above with layers of sandstone, fine, pink and green, hard, calcareous	10	530
Sandstone, coarse to fine, light gray	10	540
Sandstone, coarse to medium, light gray; layers of sandstone, fine, pink and green, hard, calcareous	20	560
Sandstone, coarse to fine, gray	35	595
Sandstone, coarse, gray; pyrite	10	605
Sandstone, very fine to medium, gray, shaly, non-calcareous	2	607
Sandstone, coarse to fine, gray, some layers pink	3	610
Sandstone, very coarse to fine, gray	20	630
Sandstone, medium to fine, gray	15	645
Sandstone, medium to fine, pinkish gray	5	650
Sandstone, fine, gray, shaly	30	680
Sandstone, very coarse to fine, pink	5	685
Sandstone, coarse to fine, gray	5	690
Shale, dark pink	5	695
Sandstone, very fine, pink	20	715
Sandstone, coarse to fine, gray	5	720
Shale, pink and red to pre-Cambrian	13	733
Total thickness	368	.....

that exposed at the surface near Baraboo and Waterloo, Wisconsin. At a number of places in Wisconsin these buried mountains rise high enough to cut off part or all of the water-bearing strata; such is the case at Hartford, Kewaskum, Two Rivers, and in part of Fond du Lac.

Possible Keweenawan sandstone.—No igneous or metamorphic rocks have ever been reached in northern Illinois, or on the Lake

[1] I. A. Lapham, Geological map of Wisconsin, 1869. Samuel Weidman and A. R. Schultz, *op. cit.*, map.

Michigan shore as far north as Sheboygan, Wisconsin. Deep wells in this belt are reported to find a red sandstone below the light-colored Cambrian, suggesting that possibly a Keweenawan sandstone fills the Michigan trough as one does the Lake Superior syncline. It is well established that the Keweenawan red sandstones of Lake Superior extend southwest into Minnesota below the Cambrian.[1] Few samples have been obtained from these rocks since, on account of the poor water which they yield, wells are no longer drilled deep enough to reach them.

[1] C. W. Hall, O. E. Meinzer, and M. L. Fuller, "Geology and Underground Waters of Southeastern Minnesota," *U.S. Geol. Survey Water Supply Paper 256*, (1911), pp. 32, 48. F. T. Thwaites, "Sandstones of the Wisconsin Coast of Lake Superior," *Wisconsin Geol. and Nat. Hist. Survey Bull. 25*, (1912), pp. 58–61.

THE STRUCTURAL GEOLOGY OF BRITISH MALAYA

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In the *Geographical Review* for July, 1921,[1] I published a short paper on the physical geography of the southern part of the Malay Peninsula, which is almost the same as "British Malaya": it has been suggested that a paper on the structural geology of the same country would be of interest. This paper therefore is an attempt to give a brief outline of the geological structure of British Malaya, an attempt which is now possible, though the detailed geological survey of every state has not been completed.

The table on page 557 is a statement of the geological sequence in so far as it is known at present, beginning with the youngest rocks:

Most of these rocks, if not all, have their counterpart in the Dutch East Indies. The granite and associated igneous rocks extend to them where a similar view is now held of the date of intrusion, i.e., the late Mesozioc. The three small patches of Tertiary rocks are but outliers of a great development of similar rocks in Sumatra. Both the younger volcanic rocks (Group 4) and the Pahang Volcanic Series are represented also in Sumatra, as also are the quartzites and shales and the calcareous group.

The Malay Peninsula belongs to a region of strongly marked coulisses[2] that sweep boldly round through the Malay Archipelago in a north easterly direction, on to the Philippines. They are arcs formed at the close of the Mesozoic Era.[3] This wrinkling of the earth's crust permitted the intrusion of large masses of plutonic

[1] *Geographical Review* (New York), Vol. XI (1921), pp. 351–71.

[2] This word "coulisse," used by Suess in his *Face of the Earth* and now by some Dutch geologists in the Malay Archipelago, is applicable to the Malay Peninsula because there the structural features are distinctly "*en échelon*" like the wings of a theatrical stage. But for this arrangement, the term "arc" is preferable as being more familiar. "Coulisse" figures in French and English dictionaries, but is not in common use, even among geologists.

[3] See Professor W. H. Hobbs, *Earth Evolution and Its Facial Expression*, p. 147.

1. Recent alluvium; particularly extensive on both the coasts of the Peninsula.
2. High-level alluvium; in Singapore, Johore, and perhaps in the Kinta District of Perak; raised beaches in several localities may be tabulated in this group.
3. Tertiary bedded rocks, probably Miocene, with coal. Only three small patches of these rocks are known.
4. Dolerite, rhyolite, and quartz-porphyry; extensive outcrops on the coast of Pahang and Johore. The dolerite, and in one case quartz-porphyry, is certainly younger than the granite. There is some doubt about the age of the rhyolite.
5. Granite, hornblende-granite, syenite, and small exposures of gabbro and norite. Small exposures of diorite may belong to this group.
6. Extensive quartzites and shales in which two definite horizons have been found. In Perak and Kedah shales contain Triassic fossils; in Pahang and Singapore fine-grained sandy beds have yielded a Rhaetic fauna (Myophoria Sandstone). In Singapore Upper Gondwana plant-remains have been found with marine mollusca first described as probably on the horizon of the Inferior Oolite.[1] In the Kinta District of Perak, clays with boulders may be tabulated here. Chert pebbles are common in the coarser quartzites.
7. Quartzite with interbedded radiolarian chert, occurring in Negri Sembilan and believed to be the lowest part of the quartzite and shale series.
8. Chert and shales; extensive in Kedah and Pahang, and occurring elsewhere. They mark the beginning of the shallow water conditions under which groups 6 and 7 were deposited. In Perlis poorly preserved *Fusulinidae* have been found in chert, but this may be silicified limestone not belonging to this group.
9. Extensive calcareous shales and limestone with some non-calcareous beds. The limestone has yielded a definite Viséan fauna[2] in the Kuantan District of Pahang, and Carboniferous fossils elsewhere.

A contemporaneous series of volcanic and hypabyssal rocks called the Pahang Volcanic Series. Exposures are extensive in Pahang and Kelantan. The series ranges from rhyolites to dolerites. Agglomerates and tuffs are particularly widespread.

10. Quartzite and shale with limestone bands overlain comformably by 9 in the Langkawi Islands. It is probable that rocks in Patalung (Lower Siam) with fossils belong to this group. The fossils were first described as Permo-carboniferous,[3] but have been re-examined and determined as probably Lower Carboniferous.[4]

[1] The fossils found in Singapore have been described by Mr. R. B. Newton who is now preparing a new paper on the subject.

[2] Described by Dr. Stanley Smith; his report has been published only in Malaya.

[3] Professor McKenny Hughes, *Rep. Brit. Assoc.*, Glasgow, 1901, p. 414.

[4] F. R. Cowper Read, *Geol. Mag.*, 1920, pp. 113–20 and 172–78.

rocks; in British Malaya these are chiefly granite, which yields the wealth of tin-ore with which the country is endowed.

Figure 1 is a sketch-map showing the coulisses in the Malay Peninsula and their probable connection with coulisses in the Malay Archipelago. The latter coulisses are taken from a paper by Van Es.[1] The dotted line shows the sweep of the arc as given in Figure 72 on page 147 of Professor Hobbs' work. My sketch-map shows that this arc is really a band in which are many small folds.

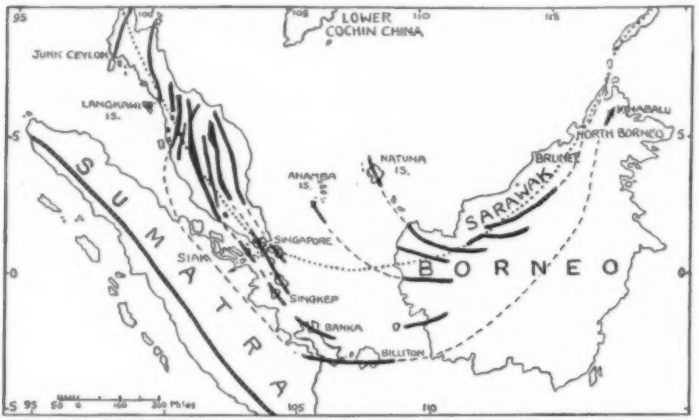

FIG. 1.—Sketch-map showing coulisses in the Malay Peninsula and Archipelago. The dotted line is the Peninsular-Bornean arc as shown in Fig. 72, p. 147, of Professor W. H. Hobbs' *Earth Evolution and Its Facial Expression*. The sketch-map shows that the arc is really a band containing many small folds.

Figure 2 shows in some detail the coulisses in British Malaya. The basis of the structure of the country may be described as a number of granite ribs or ridges occupying anticlines or more complicated folds in the older rocks, and connected in depth with a granite bathylith. These granite ribs, it may be argued, are in themselves so substantial as to merit the name of bathyliths, but their elongated form and small lateral extent make me think the term inapplicable.

[1] L. J. C. Van Es, "De tektoniek van de westelijke helft van den Oost-Indischen Archipel," *Jaarboek van het Mijnwezen in Nederl. Oost-Indië*, Vol. XLVI, Part II (1917), pp. 5–143.

FIG. 2.—Sketch-map showing the coulisses of British Malaya. The crosses indicate granite. 1. The Nakawn Coulisse. 2. The Kedah-Singgora Coulisse. 3. Gunong Perak. 4. Kedah Peak. 5. Penang. 6. Province Wellesley hills. 7. The Bintang Coulisse. 8. The Kledang Coulisse. 9. The Kerbau Coulisse. 10. The Benom Coulisse. 11. Mount Ophir. 12 and 13. The Tahan Coulisse, continued in Singapore. 14, 15, 16. The East Coast Coulisse.

The line from 3 to 10 joins the highest points of the granite ridges in each coulisse that it touches. Along this line from 3 to 9 there is a continuous granite outcrop, which is the roof of the bathylith that forms the foundation of the granite ribs, or coulisses of the Peninsula. In other parts of the Peninsula the country between the coulisses is composed of bedded rocks, shale and quartzite, or calcareous rocks, except for occasional small outcrops of granite, dolerite, rhyolite, and the Pahang Volcanic Series.

The form of the folding that led to the formation of the granite ribs cannot yet be said to be fully elucidated. The strata older than the granite are everywhere much disturbed. In the least disturbed area, the center of Pahang, the rocks are thrown into fairly sharp anticlines and synclines: in other areas they are squeezed together, pressed into a vertical position, contorted, and faulted. There is reason to suppose that the granite invaded a number of shattered anticlinoria, but in two localities there is some evidence of overfolding, with the pressure exerted from the WSW. One of these localities is in the Kinta District of Perak.[1] Here the Carboniferous limestone shows signs of great disturbance. Near Ipoh are pinnacles showing excellent examples of fault-breccias; in one crinoid-stems have been drawn out into threads in a thrust-plane. But not far distant from these pinnacles is a cliff-section which shows evidence of an overfold. The other locality is the western slope of the Tahan Range in Pahang, where the dips show a probability of similar overfolding, but the evidence is not so clear as in Kinta. However, these two localities are the only places known to me where overfolding is evident or suspected. The balance of evidence is of compressed, plicated, and faulted anticlines and synclines.

Faulting of the strata I believe to have taken place on a large scale, accompanied by "magmatic stoping." The evidence for the latter will be mentioned in the more detailed description of the coulisses.

Denudation in Tertiary and recent times has laid bare the skeleton of the Peninsula, but it has not reached the granite or associated plutonic rocks everywhere, therefore the Peninsula, apart from the difficulties created by the vegetation, forms an admirable field for observing the form of the upper limits of the granite ribs, and the way in which the granite surface plunges along its strikes under stratified rocks, is capped by them, emerges as small outcrops, or sends out veins into the stratified rocks.

In the northern portion of the map (Fig. 2), is seen the southern end of the Nakawn coulisse. I have examined this only on the Perlis border, and in what may be its prolongation in the Langkawi

[1] Ipoh, marked on the map, Fig. 2, is in the Kinta District.

Islands. A view of the Nakawn hills, however, from the railway in Siamese territory, suggests that they are granite. On the Perlis border granite is found in the north (Gunong China, 2,370 ft.), but it plunges under a thick cover of limestone, which forms rugged hills along the border to the sea. This range of limestone hills contains, near the granite, deposits of tin-ore that are worked in caves. It curves slightly toward the west before it reaches the sea, which suggests that the similar rugged limestone hills of the Langkawi Islands are part of the same coulisse. In these islands, however, granite reappears in Gunong Raya (2,888 ft.) and other outcrops.

The Kedah-Singgora Coulisse (No. 2) is a broader range of shale and quartzite hills of no great altitude, in which a few outcrops of granite have been found, but Bukit Tinggi, the principal peak (2,525 ft.), is formed of the sedimentary rocks. Tin and wolfram deposits in its neighborhood prove, however, that granite cannot be far below the surface. These hills extend northward to the China Sea, and are crossed in Siamese territory by the railway to Kelantan. Cuttings on this railway show a large granite outcrop between outcrops of quartzite.

South of the range are isolated outcrops which may have once been continuous with it, but have been separated by marine denudation, converting them into islands in a sea covering the plain of Kedah and Province Wellesley. The first of these (No. 3) is Gunong Perak (2,823 ft.), an isolated granite mass. Number 4 is a more imposing mountain, Kedah Peak or Gunong Jerai (3,978 ft.), formed of quartzite with granitic intrusions. Penang (No. 5) is still an island. The only rock other than granite that I have seen there is dolerite, and I have not seen that in situ. The main mass of the island is certainly granite, rising to 2,722 ft.; but to the southeast are two small islands of sedimentary rocks. In Province Wellesley are granite hills with a few of sedimentary rocks also.

The Bintang Coulisse (No. 7) is the first large granite range in this part of the Peninsula. It has been broken by marine denudation between Taiping and the Dindings, and farther north, between Gunong Bintang (6,103 ft.) and Gunong Lang (3,750 ft.) is a comparatively low tract of stratified rocks, the granite being seen only

in low country to the west of it. In the headwaters of the Patani River the granite hills continue and end west of the Patani River near the sea.

Near Taiping are two interesting outcrops of limestone. On the west of the Bintang Coulisse is a limestone hill, Batu Kurau, nearly surrounded by granite. On the east of the coulisse is a better-known limestone hill, Gunong Pondok, visible from the railway, which may be entirely surrounded by granite: a covering of alluvium on one side makes this doubtful.

The largest granite range of the Peninsula is that generally known as the Main range (No. 9, the Kerbau Coulisse; Gunong Kerbau 7,160 ft.), and between it and the Bintang Coulisse is a small granite range (No. 8, the Kledang Coulisse) which dips under altered sedimentary rocks at either end. At the northern end of this range are two peaks, Gunong Soh (4,336 ft.) and Gunong Besar (5,725 ft.), but this granite dips under schists and sheared quartz-porphyry of the Pahang Volcanic Series immediately north of the east-and-west reach of the Perak River (see map). Gunong Soh and Gunong Besar are the highest peaks in this granite mass and are connected by low-lying granite areas with the Bintang Coulisse on one side, and the Kerbau Coulisse on the other. Farther south there is a break in the granite hills where a tributary of the Perak River cuts through the range north of Kuala Kangsar. Here the granite almost entirely vanishes below the surface: a strip of older sedimentary rocks and one of the small patches of Tertiary rocks (containing limestone) break the continuity of the granite except for a small exposure in the Perak River. Both in this range and in the Bintang Coulisse there is evidently a dip in the profile of the granite ridge. In the Bintang Coulisse it involves a drop on the steeper side of about 5,000 feet in 8 miles, an incline of roughly 1 in 8; in the Kledang Coulisse there is a drop on the steeper side of about 2,000 feet in 2 miles, an incline of roughly 1 in 5.

Farther to the south the granite of the Kledang Range, forming peaks of between 2,000 and 3,000 feet, dips under quartzite, which forms a lower continuation of the range until it dies away in the alluvium of the Perak River.

In the country between the north part of this Kledang Coulisse and the Bintang Coulisse, an area that is low-lying, there is, as

already stated, granite connecting the two. In this granite there are, in the neighborhood of Lenggong, about 30 miles north of Kuala Kangsar, small hills of crystalline limestone surrounded by the granite, which appear to be portions of the Carboniferous limestone stoped away from the cover and prevented from sinking farther by the viscosity of the magma. They contain secondary minerals commonly found at such contacts.

Farther to the south, in the Kinta District, mining operations in the valley of a stream, the Johan, that rises in the Kledang range, have revealed another island of limestone in the granite.

The Kerbau Coulisse (No. 9) is the most arcuate of all those in the Peninsula, a pronounced bend existing about half-way along its course. The northern half is the higher, with several peaks above 7,000 feet and along part of the northern half the descent is steeper into Kelantan than into Perak.

In the extreme north, in the neighborhood of Tomo, the details of the coulisse are not yet accurately known, but south of Tomo recent journeys have brought to light an interesting structural point. On the map a sharp curve can be seen in the boundary between Perak and Kelantan, about twenty miles south of Tomo. Here a granite mountain, Gunong Noring (6,194 ft.) visited in 1922 by Mr. H. E. Savage, is, approximately, the end of the granite outcrop along the watershed. A little north of Gunong Noring the granite outcrop bifurcates, one fork passing through the headwaters of the Perak River into Siamese territory between the Patani and Telubin rivers, the other trending northeast. Part of the intervening country is still unsurveyed, but it is believed that the northeast branch ends in hilly country east of Tomo. In between these two forks of the granite ridge are altered sediments with small outcrops of granite-aplite, hornblende-granite, and diorite, evidently apophyses from the main mass below the sediments.

In both forks the granite is often gneissose owing to flow in the magma. It is rich in biotite; and in the western fork I have found a large outcrop crowded with xenoliths of mica-schists, showing that denudation has not removed much granite.

The highest portion of the granite ridge in the Kerbau Coulisse is in the neighborhood of the junction of the boundaries of Perak, Kelantan, and Pahang. Here are three peaks of over seven

thousand feet, and a little farther north are two more. Of the three near the junction of the state boundaries, one, Kerbau (7,160 ft.) is known to be capped by altered sediments, so that on this mountain we have the original limit of the granite ridge.

Farther south than Kerbau, just on the bend of the coulisse, a large outcrop of schists and quartzite is known on the Pahang side at an altitude of three to four thousand feet, surrounded by granite; and on the opposite side of the range, at Chanderiang, a long tongue of limestone, under alluvium worked for tin-ore, is almost surrounded by granite. Farther south still, in Selangor, there is another outcrop of calcareous rocks in the granite at Kanching, part being a prominent limestone hill, and also an outcrop of altered sedimentary rocks in the granite near Kuala Kubu.

In the southern half of the Kerbau Coulisse the granite hills fall away gradually. Near the bend Batu Puteh is 6,987 feet. Near the Selangor border Gunong Liang is 6,431 feet; in Selangor Ulu Kali is 5,820 feet. In Negri Sembilan the mountains are under 4,000 feet, and in Malacca they die away altogether; but the coulisse is continued to Banka, the intervening gaps being caused by marine denudation.

In Selangor and Pahang tin-deposits are found high up in the mountains of this coulisse, in some cases on the watershed. As tin-deposits in a granite mass are generally peripheral, this suggests that little granite has been removed from the top of the ridge by denudation.

On the east side the Kerbau Coulisse is flanked in Pahang by a well-defined range of quartzite foothills. Beyond this, at Raub and to the north and south of Raub, the calcareous series is exposed over a wide area until the Benom Coulisse is encountered. The calcareous rocks are found to the east of this coulisse also, in the wide valley of the Pahang River, and are there covered in places by sandstone and shale in which there is a Rhaetic horizon, the Myophoria Sandstone described by Mr. R. B. Newton.[1] In the Benom Coulisse the only high peak is Gunong Benom, 6,916 ft. The rock is mostly hornblende-granite; there is some syenite. To the north the plutonic mass disappears under the sedimentary and calcareous

[1] *Proc. Malacological Society*, Vol. IV, Part 3 (October 1900), pp. 130–35.

rocks before reaching the Kelantan border, a few small outcrops of granite and granite-porphyry only being found. To the south it continues into Negri Sembilan, where it disappears under the calcareous series close to the granite of the Kerbau Coulisse. Hornblende-granite has not been found at this end, but Mr. E. S. Willbourn mentions boulders of quartz-diorite.[1]

Beyond the Kerbau and Benom Coulisses is Mount Ophir (No. 11), 4,187 feet. This is an isolated mountain of granite, but, it may be assumed, connected at no great depth with the granite of the Kerbau Coulisse, which, in turn, must be connected at no great depth with the granite of the Benom Coulisse, the last-named being best regarded as a large spur given off by the Kerbau Coulisse.

To the north of the Benom Coulisse there is a large tract of country in Kelantan that has been only partially explored. In the vicinity of Pulai muscovite-aplite intrusive in limestone may be connected with the Benom granite. Farther north, in the branch of the Kelantan River rising in the Kerbau Coulisse, and on the line of strike of the Benom granite, pyroxene-granite-porphyry, biotite-granite, and pebbles of a hornblendic rock, probably diorite, have been found in country largely consisting of limestone. If the line of strike is continued farther still, it joins the Kerbau Coulisse south of Tomo, and in the neighborhood of Tomo are the small intrusions of diorite and hornblende-granite mentioned above. This line of strike of the Benom granite, from Negri Sembilan in the south, through Pulai, to Tomo in the north, passes through the gold-bearing belt of the Peninsula, which is sharply differentiated from the chief tin-bearing belt to the west. Much of the gold has been derived from rocks of the Pahang Volcanic Series, but some is found in country where the hornblende-granite and diorite occur, these appearing to be the source in certain areas. Continued work may reveal something more definite about the relation of these hornblendic rocks in Kelantan to the granite of the Kerbau Coulisse and the rocks of the Benom Coulisse.

East of the Benom granite in Pahang and in the country about Pulai in Kelantan, limestone is abundant, but it ends abruptly

[1] "An Account of the Geology and Mining Industries of South Selangor and Negri Sembilan," *Geol. Dept. F.N.S.*, 1922, p. 35.

against a broad outcrop of quartzite forming rugged hills and rising, on the Pahang-Kelantan border, to a height of 7,188 feet (Gunong Tahan, the highest mountain in the Peninsula). This mass of quartzite (No. 12) falls away to the north of the Pahang-Kelantan border, but southward it extends beyond the Pahang River. In the extreme south of Pahang and in Johore granite hills occur, and outcrops of quartzite also, which are assumed to form a continuation of this "Tahan Coulisse"; and in Singapore Island the granite and quartzite appear again, the latter weathered to sandstone with Myophoria and other fossils.

In the south this band of quartzite and granite is broken by marine denudation. There are certainly intrusions of granite. In the north the outcrop of quartzite is rugged, continuous, and on the Pahang-Kelantan border, very high, but I have not seen any granite outcrops in it, or any veins of aplite, or evidence of the proximity of granite, such as tourmalinization. The nearest granite known to me is a small outcrop close to the western edge of the quartzite east of Pulai, but it is intrusive into limestone country. It may be that, in the northern part, this mass of quartzite owes its prominence simply to its power of resisting denudation, but there is, as already mentioned, some evidence of folding, and in view of the fact that the prolongation of the Peninsula to Singapore is due to its existence and that of the hills marked 14, 15, 16 in Figure 2, I think it is justifiable to name it the Tahan "Coulisse."

The last of the ribs of the Peninsula is that marked 14, 15, 16 on the map. This may conveniently be referred to as the East Coast Coulisse. Recent work shows that in the north it is a definite granite range rising in Kelantan close to the sea. The granite certainly extends a long way down the Trengganu border, and it is believed that it reaches the Pahang border, where the coulisse is continued in hilly country of granite and altered sedimentary rocks. These are broken by the alluvial plain of the Pahang River, but continue to the south as hills of sedimentary rocks with at least one granite outcrop. On the Johore border large outcrops of granite are known, and in Johore the coulisse is continued as more outcrops of granite and sedimentary rocks, with volcanic rocks of undetermined age, until it ends in the point east of Singapore. The

granite of this coulisse is tin-bearing in the north of Pahang, the South of Pahang, and in some localities in Johore. Tin and wolfram deposits in Trengganu are probably connected with it, and in Kelantan a little tin-ore is reported in it. It forms another tin-bearing belt, not so well-defined as that formed by the Kerbau Coulisse and other coulisses to the west of it. The gold-bearing belt lies between the two.

The island of Tiuman consists mostly of granite. The numerous small islands nearer the coast are of rhyolite and granite.

The Peninsula then has a skeleton of granite ribs from which denudation has not yet removed the whole covering of bedded rocks. In some cases, such as those marked on the map as Nos. 1 and 2, the thickness of the cover remaining is considerable. In No. 9, the Kerbau Coulisse, a small portion of the cover remains perched at an altitude of 7,000 feet. Islands of schists and quartzite are known at lesser elevations in No. 9, and masses of limestone are found totally surrounded by granite on the surface in Nos. 9 and 8, all parts of the cover.

These granite ribs are arranged *en échelon:* no one range can be said truly to be the backbone of the Peninsula; but if we refer to Figure 1, or Figure 72 on page 147 of Professor Hobbs' book, we see that they are but the detailed wrinkles of one great band of folding that sweeps through the Peninsula and then, turning NE, through the northern part of Borneo to the Philippines.

Owing to the amount of the cover remaining, one can obtain a fairly good idea of the profiles of the granite ribs when they first consolidated. In Figure 2 I have drawn a line through some of the coulisses, connecting the highest outcrops of granite. This line, starting at No. 3 (Gunong Perak, 2,823 ft.), and extending as far as Benom, will be seen to have the same general direction as that of the curve of the arc through the Peninsula and Borneo just referred to. The line might be produced in the same direction to No. 13 (Gunong Besar, 3,403 ft.) but there is some doubt about its being all granite. In the East Coast Coulisse the highest granite is far to the north of Gunong Besar. This line, however, joining the highest parts of the granite profiles of 3, 7, 8, 9, and 10, is interesting as showing the probable trend of the first emergent

land when the denudation of the cover began, which was, as far as we can tell, in late Mesozoic times (in the Archipelago Eocene beds contain granite pebbles). To the east, the quartzite of the Tahan massif and the granite of the East Coast Coulisse formed another mass of superior resistance determining the extension of the land in that direction.

In my paper in the *Geographical Review* I sketched the history of the Peninsula and Archipelago in Tertiary and recent times (pp. 353, 354). In Miocene times there is reason to believe that depression converted the Archipelago into a few small islands and that later "a gradual elevation occurred which ultimately united the whole of the islands with the continent."[1] This depression must have affected the area that is now British Malaya, and it was marine denudation connected with this depression, then subaerial denudation when the uplift occurred, and marine denudation connected with another depression in recent times, that revealed the true course of the granite intrusions, and made the breaches in the Bintang and Kledang Coulisses where the granite dips under the older stratified rocks. In the case of the Kledang Coulisse, if the patch of Tertiary rocks occurring in the gap is Miocene, the breach was effected in Miocene times.

The effect of marine denudation has been great. It is particularly noticeable in Johore, where the granite and other hills rise like islands from a gently undulating plain, and in Perlis and Kedah, where some of the hills are even more striking in their resemblance to islands.

In the basin of the Perak River there is, above Kuala Kangsar, evidence of the continuity of the granite between the coulisses. The granite of the northern end of the Kledang Coulisse (No. 8) is connected on the surface with that of No. 9 on the one hand and that of No. 7 on the other. The granite of Gunong Perak also (No. 3) is connected by comparatively low-lying outcrops with that of the Bintang Coulisse, but elsewhere the granite outcrops of one coulisse are separated from those on either side by stratified rocks.

The granite outcrop connecting Gunong Perak with the Bintang Coulisse strikes only a little to the north of Gunong Bintang, the

[1] Dr. A. R. Wallace, *Island Life*, pp. 385, 386, 390.

highest point; so here we have a continuous granite outcrop from Gunong Perak to a part of the Kerbau Coulisse where there are two peaks of over 7,000 ft. Between Nos. 9 and 8 the country is fairly high on the granite outcrop, but between 8 and 7, and 7 and 3, it is only about 300 feet above sea-level.

The strike of this continuous granite outcrop, across the coulisses, is, as can be seen from Figure 2, on which I have shown the granite by a conventional sign, roughly parallel to the axis of the Peninsula, and to the curve of the Peninsular-Bornean arc, and shows the roof of the bathylith (containing near Lenggong, as already noted, isolated blocks of limestone from the cover). Between 9 and 10, however, the granite dips steeply under the older bedded rocks near the line of highest granite points. The land is not high: Raub is only 462 feet above sea-level, Bentong only 321, but at Raub a shaft 900 feet deep shows no granite, or signs of its proximity, other than the occasional occurrence of scheelite in the gold-bearing veins. In the Benom Coulisse it rises again sharply and falls away sharply on the other side under the Pahang Valley.

Granite is not entirely confined to the coulisses on the surface. In the low country between them small outcrops are found. Some form distinct landmarks, for instance a hill at the mouth of the Selangor River, and another on the coast near Kuala Lumpur.

The composition of the granite and other igneous rocks in the coulisses raises interesting problems that would be out of place to discuss here. I will mention one point in this connection only, that the summit of Kinabalu (13,698 ft.) at the far end of the Peninsular and Bornean arc, is formed of hornblende granite.

There remains one point in the structure of the Peninsula to be mentioned, the influence of faulting in the cover of stratified rocks on the formation of limestone hills, which sometimes exceed 2,000 feet in height. The limestone hills I have mentioned in a granite-area near Lenggong, and again at Kanching, and those almost surrounded by granite, Batu Kurau and Gunong Pondok, suggest block faulting; but the majority of the limestone hills are not in the granite-areas. The greatest development of them is found in the Kinta District, where their distribution and height above the limestone floor of this tin-field suggest block-faulting on a large

scale, and the suggestion is strengthened by vertical limestone cliffs overlooking the granite of the Kerbau Coulisse, by small patches of phyllites lying between the base of these cliffs and the granite, and by a brecciated iron-ore deposit at the base of one of the hills. In Perlis again a double line of limestone hills runs north and south through the center of the state, rising from shale and quartzite country, but here there is a possibility of the latter being older than the limestone. In other states I have not seen any evidence of faulting having formed blocks which denudation has converted into limestone hills. I may mention in this connection that Dr. W. C. Klein, who has studied the geology of northern Sumatra, where limestone hills also occur, tells me he considers that faults are of structural importance and affect the limestone. In Borneo also, the late Mr. J. S. Geikie attributed the formation of the limestone hills of the gold-bearing area of Bau and Bidi in Sarawak to faulting.[1] I have seen the limestone hills at Bau and Bidi and found the evidence of faulting determining their formation very strong, and clearer than in the Kinta District, where the earth-movements have been more intense.

In Sumatra Dutch geologists recognize earth-movements later than the Mesozoic folds. In the Peninsula these are marked by faults in the granite, and in some places, as in Negri Sembilan, by shearing of the same rock, but they are not known to be of any structural importance.

[1] J. S. Geikie, "The Occurrence of Gold in Upper Sarawak," *Trans. of the Inst. of Mining and Metallurgy*, Vol. XV (1905–6), pp. 65, 66 and Fig. 1 on p. 65.

THE FERRUGINOUS CHERT FORMATIONS OF NOTRE DAME BAY, NEWFOUNDLAND[1]

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OUTLINE

SUMMARY
FIELD WORK
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- Ordovician
- Silurian

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VARIETIES OF CHERT, AND ASSOCIATED ROCKS
- General Statement
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- Comparison with Other Regions
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  - Source of the Solutions
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SUMMARY

This paper describes ferruginous cherts which for the most part are found as beds of very uniform thickness in sections composed largely of volcanic rocks. The author considers the cherts to be chemically precipitated sediments.

[1] Part of a thesis submitted to the faculty of Princeton University in candidacy for the degree of Doctor of Science, 1920.

The rocks of the region vary from Cambrian to Silurian age and are, for the most part, of volcanic origin, pillow lavas being abundant and developed to great perfection. The author believes that widespread pillow lavas, such as are found in Notre Dame Bay, are formed by subaqueous extrusion.

There are three types of chert. The first is found in the interstices of pillow lavas, the second as heavy beds of jasper found with acid tuffs, and the third as thin beds interbedded with acid tuffs. The bedded chert contains radiolaria but only as incidental fossils. Cherts of these varieties have been described from many parts of the world and some of the more important occurrences are cited. The geologic occurrence in every instance presents features in common with those of Notre Dame Bay. Particularly is this so of the radiolarian cherts of Scotland.

The silica of the cherts is thought to have been contributed to a marine basin principally by magmatic emanations from submarine vents or fissures. Processes are suggested by which precipitation might have been brought about, the most important being the precipitation of colloidal silica by the ions of sea water having an opposite charge and, to a less degree, by oppositely charged colloids formed by the interaction of magmatic and sea water.

FIELD WORK

This paper is a report on a portion of the field work carried out by the Princeton University Geological Expeditions to Newfoundland of the years 1915, 1916 and 1919. Most of the work was of a reconnaissance nature covering Notre Dame and White Bays. In 1919 Notre Dame Bay was revisited and detailed work was done. Though most of the work was on the copper mines, special attention was given to the chert localities.

ACKNOWLEDGMENTS

It is a pleasure to make the following acknowledgments. Dr. Arthur F. Buddington and Dr. William M. Agar were both associated in part of the field work. They made the work possible and have contributed much in discussion of the geology of the region. Mr. Allan C. Brown and Mr. Hiram Blauvelt were each in the field

one season and cheerfully and efficiently assisted in the work. Professor Gilbert van Ingen, who organized the Princeton University Expeditions to Newfoundland, has by the stimulus of his interest aided the work of which this report represents a phase. Dr. Rudolph Ruedemann has identified and correlated the grapolites. This report was written under the direction of Professor C. H. Smyth, Jr., and it is a pleasure for one of his former students to acknowledge the inspiration of his teaching and influence, even though this paper so little reflects it.

GENERAL GEOLOGY

A map showing the general location and some details of the geography as copied from British Admiralty charts is given in Figure 1.

The general distribution of the rocks in Notre Dame Bay is such that the oldest formations are found on the north side of the bay and on the outer headlands of the west and south sides. Going inland, south and west, up the fiord bays younger formations are encountered of Ordovician and Silurian age. At a few places in these younger formations highly fossiliferous rocks are found. Professor van Ingen reports that all faunas show a marked affinity to those of Great Britain, and range in age from Llandeilo of the Ordovician, to Llandovery, or perhaps Wenlock, of the Silurian. The similarity of the geologic history of these two regions in Ordovician and Silurian time is remarkable.

Throughout the whole district the structure is exceedingly complex. Faulting is highly developed, but folding is not conspicuous and is seldom observed although dips are high, often vertical.

Several series of rocks can be recognized, the oldest being volcanic.

CAMBRIAN (?)

One great series is composed very largely of andesitic pillow lava with minor amounts of basic breccia and tuffs of variable composition. Ordinary sediments appear to be lacking. Chert is often found on the spaces between the pillows, and also with heavy beds associated with tuffs. In places there are exposed great sections of tuffs, breccias, and flows which show no pillow

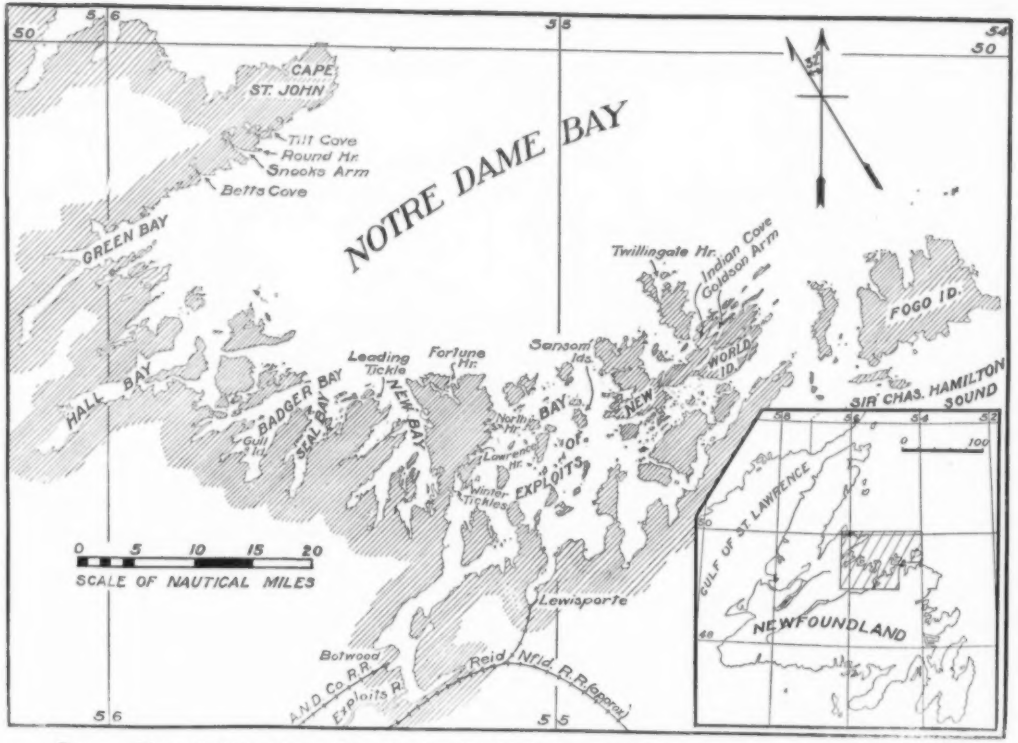

FIG. 1.—Map of Notre Dame Bay, Newfoundland, showing localities mentioned in text. Based on British Admiralty charts.

structure. Such sections do not contain chert. These sections are not simply different facies of the pillow lava series, but are thought to represent a distinct series. As to the age of these two series, evidence is scanty. That the first mentioned series containing chert is considerably older than the Upper Ordovician is indicated by the relative degree of metamorphism, and particularly by the finding of its characteristic green chert in conglomerates of Upper Ordovician age. This series is probably of Cambrian age. As to the other series which does not contain pillow lavas or chert, we can only say that it is intermediate in age between that of the old pillow lavas and the Middle Ordovician.

ORDOVICIAN

The known Ordovician rocks are represented in the lower sections by volcanics and shales. The volcanics are principally pillow lavas of andesitic composition and tuffs which are mostly acid. Throughout Notre Dame Bay rhyolite flows are practically absent, the rhyolitic eruptives being clastic and represented principally by tuffs which show somewhat waterworn fragments. Thin beds of chert are often found associated with these tuffs. In some places, the volcanics are wanting, and shales containing beds of chert take their place, though a persistent black graptolitic shale fixes the age of these rocks as contemporaneous with sections showing volcanic products. The graptolites are of Llandeilo age. In the higher sections, there are sandstones and some conglomerates, both of which are commonly red. In places on the east side of New World Island, limestones of Caradoc age are associated with pillow lavas and volcanic breccias, some of which breccias have a lime cement. At Burnt Arm, branching from Goldson Arm, a pillow lava was seen with fossiliferous limestone in the spaces between the pillows. The lime mud must have been caught up when the lava was extruded. Here, at least, the evidence for the subaqueous nature of the pillow flows is clear.

SILURIAN

The Silurian rocks are principally sandstones and conglomerates, usually red. Very thick sections are exposed, those studied being in the extreme south of the bay and on the Exploits River. They are

FIG. 1.—Map of Notre Dame Bay, Newfoundland, showing localities mentioned in text. Based on British Admiralty charts.

in places highly fossiliferous. Volcanic rocks are almost entirely absent in the known Silurian. No chert has been found in the Silurian or in the upper part of the Ordovician.

Intrusive igneous rocks are abundant and varied and greatly complicate the structure of the region, but as they have no bearing on the present problem they need not be discussed.

DISTRIBUTION OF CHERTS

The area in which the cherts occur on the coast is clearly limited, as they are confined to that portion within which the pillow lavas are found. The pillow lavas are thick conspicuous formations which in this part of the Newfoundland coast do not occur north of Cape St. John nor east of New World Island. Within Notre Dame Bay they are exposed at many places.

VARIETIES OF CHERT AND ASSOCIATED ROCKS

GENERAL STATEMENT

Wherever the cherts have been observed, with the exception of only one occurrence, to be considered later, they are intimately associated with volcanic rocks. Three general modes of occurrence are recognized: first, in the spaces between pillows; second, as heavy beds of jasper associated with acid tuffs; and third, as thin beds of green chert, associated with tuffs, in sections which are made up principally of fragmental material and shale. The first type, interstitial, occurs in the oldest pillow lava series of probable Cambrian age; the second type, heavy beds with tuff, is probably also of the same age; and the third type, which consists of thin beds, is in several widely separated localities in close proximity to the black graptolitic shale above referred to and is probably of the same age, Llandeilo. Pillow lavas are found in some of these sections though not in immediate association with the chert beds.

The flows of pillow lava, throughout the region, are commonly from 50 to several hundred feet thick. Individual pillows vary greatly in size, being sometimes as much as 10 feet in diameter, but the average greatest cross-section is about three or four feet. They usually approach spherical form, but quite commonly bolster-like masses are found. They are exceedingly massive and very

rarely show hollow centers. Concentric rings of amygdules are frequently seen and variolitic structure is common, the variolites increasing in size and number toward the center where they coalesce to form a dense crystalline rock. Variolites are seldom over a centimeter in diameter, and in most cases but a few millimeters. The variolitic shell ranges in thickness from a few millimeters to 10 or 15 centimeters or even more. Pahoehoe lava and the various ropy forms so characteristic of subaerial flows are absent. In Notre Dame Bay pillow lavas are probably shown in as great perfection and profusion as in any other region yet described.

Although recognizing that pillow lavas may form on a small scale on land, the author believes that a review of the literature justifies the conclusion that a thick series of pillow lavas, covering a wide area and free from pahoehoe and massive flows, is in all probability a subaqueous flow, and such an origin is accepted for the pillow lavas with which the cherts in question are associated.

FIRST TYPE—INTERSTITIAL

The first type of chert to be considered in detail is that which occurs in the spaces between the pillows. The chert is found in irregular masses conforming to the pillow surfaces and seldom over eight inches in greatest dimension. The chert does not replace the surrounding rock which shows the usual gradational changes through variolitic or amygdaloidal structure to the tachylitic crust next to the chert. Good exposures of chert in pillow lava may be seen at Round Harbor, the bottom of Snooks Arm, the Betts Cove copper mine and on the southwest shore of the Northwest Arm of Fortune Harbor.

SECOND TYPE—HEAVY BEDS OF JASPER

The second manner of occurrence of the chert is in heavy beds associated with rhyolitic tuffs and forming part of the old (Cambrian?) pillow lava series. The chert in this association is usually a bright red jasper and in places it is very dark red, due to a considerable manganese content. As the associations are so much the same in widely separated localities, these rocks may form a distinct member of the series.

The jasper of this formation forms beds as much as 25 or 30 feet in thickness, though the zone through which these heavy beds occur is probably not greater than 100 feet. However, at the Southeast Arm of Fortune Harbor, where the Jasper is apparently overlaid by several hundred feet of tuff, these tuffs contain many thin beds of red and green chert a few inches in thickness.

Good exposures are to be seen at the following places: the north shore of Goldson Arm and the north shore of Indian Cove, both on New World Island, and in several places in Fortune Harbor, particularly at the two places where prospecting has been done on the beds for their iron or manganese content. There is also exposed on the trail from Round Harbor to Tilt Cove a very heavy bed of jasper apparently in the same association as the others, but at this place the very dense underbrush obscures the relations.

Some of the occurrences of this type of chert contain radiolaria. These will be described under the microscopic features.

THIRD TYPE—THIN BEDS

There remains one type to be described, the third type, which occurs interbedded with a peculiar siliceous shale and often with rhyolitic tuffs. This type of chert is exposed at the following places: the northern part of the western shore of Sansom Island; between North Harbor Head and North Harbor on the Ship Run of the Bay of Exploits; at Lawrence Harbor and also on the east side of Winter Tickle, both on Ship Run; on the south side of Leading Tickle, at and near the Ladle; and on the small islands south of Gull Island in Badger Bay.

These exposures have many features in common. The prevailing type of chert is a green variety, having a porcelain-like texture and a very perfect conchoidal fracture. In places thin beds of jasper are of minor importance. The chert is usually interbedded with tuffs.

The individual beds of chert are thin, being rarely over a foot thick, often from three to six inches thick, and in places less than one inch thick. The thickness of individual beds is of great uniformity and the beds are persistent. In this respect, as in many others, they resemble some of British radiolarian cherts of the same

age, but they are in marked contrast with those of the Franciscan Series of California. This type of chert in Notre Dame Bay commonly contains radiolaria.

The tuffs associated with the chert are composed largely of crystal fragments among which quartz usually predominates. Both potash feldspar and soda-rich plagioclase are present together with a considerable amount of fine-grained devitrified glass. All the fragments are angular and are contained in a very fine-grained ground-mass. Delicate structures such as shards of glass seem to be entirely lacking, the material probably having been sufficiently waterworn to have destroyed them. Beds of shale are common, but many of them are of a peculiar nature, perhaps originally containing some gelatinous silica. The whole chert, shale, and tuff series is frequently associated with pillow lavas.

In one place chert of the thin-bedded type is found where there are no volcanic rocks in the section, but there is reason to believe that these chert beds were formed contemporaneously with volcanism elsewhere in the district. In Badger Bay, on the small islands south of Gull Island, a section is found which resembles those of Leading Tickle and Lawrence Harbor and like them is in close proximity to beds of black graptolitic shale. On these islands thin beds of chert are well exposed, but the tuffs which form parts of the other sections are absent. However, the black graptolitic shale fixes the age as contemporaneous with the volcanic rocks of the other sections.

This section, which probably represents about 2,000 feet of sediments, is composed largely of varieties of a peculiar shale. In the hand specimen it is a hard dense rock, where cleavage is not highly developed. The commonest colors are green and gray. It is rather thin-bedded and free from carbonate. In parts of the section, portions from 50 to 100 feet thick are predominantly red and in or near these red portions thin-bedded chert is found. There is probably a considerable admixture of cherty silica in these shales.

The most interesting feature of these red shales is the great profusion of radiolaria at some horizons. The shale rich in radiolaria usually shows them in the hand specimen as light specks. These can readily be seen if the rock be smoothed off with a whet-

stone and then moistened. This test was found useful in the field. In one bed near the westernmost point of Gull Island, the radiolaria appear like abundant white sand grains in the red matrix of the rock.

The cherts of this locality show almost no radiolaria. It is believed that these chert beds were formed much more rapidly than the enclosing shales, and that they are free from radiolaria and impurities because of this rapidity of deposition.

COMPOSITION AND STRUCTURE

To avoid repetition, the green varieties of chert will be described together followed by a description of the red varieties. There is a fundamental relation between the present color of the chert and the manner in which it has been formed.

GREEN CHERT

Green chert is found in the first and third types—interstitial and thin-bedded. In both types it appears to be of much the same nature. Most thin sections show an extremely fine aggregate of interlocking grains of quartz, the largest grains in different thin

ANALYSIS OF 2-INCH BED OF GREEN CHERT (260 Y 16 *a*) FROM WEST SIDE OF LAWRENCE HARBOR, SHIP RUN, BAY OF EXPLOITS, NOTRE DAME BAY, NEWFOUNDLAND

SiO_2	85.78
Al_2O_3	5.68
Fe_2O_3	2.92
FeO	2.09
MgO	.25
CaO	.48
Na_2O	.68
K_2O	.36
$H_2O\pm$	1.88
	100 13

sections varying from about 0.05 mm. to as little as 0.02 mm. In every case most grains are considerably smaller than the largest, generally about 0.005 mm. Some sections contain isotropic silica and in these there is a gradation from the isotropic area into the crystalline area, crystallization starting at scattered nuclei.

All sections show more or less cloudiness at low magnification. At very high magnification the impurities can be distinguished as specks. They are in the form of plates and appear to have a faint green color. The index is well above quartz. Under crossed nicols most grains cannot be distinguished. One specimen of this variety of chert was analyzed. It contains more than the usual amount of impurities and was selected in the hope of shedding light on their nature. The analysis is shown on page 580.

Some of the larger grains of the green mineral in this specimen show, in addition to the above-mentioned properties, a distinct pleochroism and when seen on edge a moderate birefrigence and an extinction nearly or quite parallel. This analysis throws some light on the mineralogic composition of the chert. Most important is the amount of ferric iron. If this were not combined the rock would surely have a red color. The presence of a ferrous-ferric silicate seems clear. It may be noted that with the union of similar bases the ratio $Al_2O_3:FeO:Na_2O$ is almost precisely 5:3:1. However, as the amount of all the minor constituents is so small no great weight is to be attached to this. It is possible that the alkalies may be adsorbed by the silica. Their quantity is much less than the amount required by glauconite and the amount of alumina also points away from that mineral. There seems to be, however, little doubt that there is present an alumina-ferric-ferrous-silicate with probable alkalies. Assuming 5 molecules of silica and 6 of water, there would be present about 19 per cent by weight or 16 per cent by volume of a mineral having a density about equal to thuringite. This quantity, which is of course only a rough approximation, seems consistent with observation, though the grains are too small and their boundaries too ill-defined for exact measurement.

Red Chert

Thin sections of red chert are for the most part opaque. Some sections are entirely so, but others are not uniformly opaque. In these last the opacity is seen to be caused by extremely minute red specks of iron oxide. The distribution of these is not uniform but is without system. Most of the area is opaque, the more translucent portions being in the form of clouds within the opaque

areas. The silica in many sections is amorphous, as in the case of the green cherts. In many thin sections of the second type of chert and of the red beds of the third type radiolarian tests can be clearly seen. The tests are of clear quartz. The radiolaria are of extremely simple structure; none of them show spines, and it seems improbable that they ever possessed any. The commonest forms are spherical. Many have a clear center and consequently show no shell. They range from 0.20–0.30 mm. in diameter. Others are annular in section and about the same size. The central part of these forms is filled with opaque jasper. In the shales associated with the thin beds of chert at islands off Gull Island in Badger Bay, there is a profusion of forms having an elliptical annular section varying from 0.15×0.20 mm. to 0.30×0.50 mm. besides very abundant smaller circular forms. In these shales the radiolaria are preserved in great perfection, the boundaries being exceedingly sharp. Only one individual was observed having a slight protuberance and none were observed with any spines.

One occurrence each of the interstitial and of the heavy bedded jasper give evidence of diffusion phenomena having taken place while the silica was in a gelatinous condition. This is best illustrated by the jasper of the Sweeny manganese prospect at Fortune Harbor. Here 30 feet of jasper is to be seen, which lies between 70 feet of pillow lava and a tuffaceous sandstone probably at least 50 feet thick. About 15 feet of this jasper is manganiferous; an aggregate sample of pure unweathered jasper yielded 5.16 per cent Mn. This manganese has been further concentrated on joints.

The manganiferous and nonmanganiferous jasper of this locality show features which are interpreted as having been formed in gel. The most striking features are found in the nonmanganiferous portion illustrated in Figures 2, 3, and 4. In Figure 2 the dark areas represent opaque jasper, and the clear areas silica with cloud-like specks of iron oxide. These are shown in Figure 3 which is a portion of the same field as Figure 2. It is to be noted that all areas, regardless of size or shape, are surrounded by a clear band about 0.004 mm. thick and outside that a dark band somewhat thin-

ner. This structure is most readily explained as caused by precipitation by diffusion. The whole sectem is now composed of crystalline quartz, the boundaries of the grains showing no relation to the structure described. Another part of the same section is illustrated by Figure 4. The clear central areas contain minute cherry red plates presumably of hematite. The boundaries of these crystals

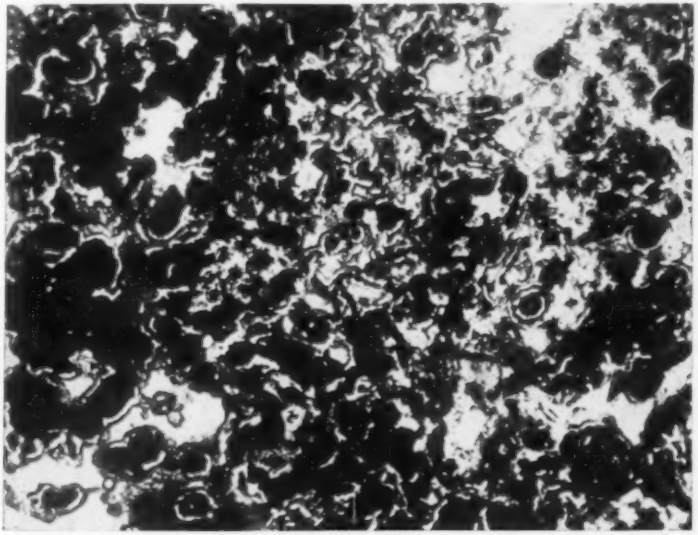

FIG. 2.—Thin section (No. 211) of jasper from Sweeny manganese prospect, Fortune Harbor. Shows banding in what is thought to have been colloidal silica. Section now composed of quartz whose crystalline structure is entirely independent of the original structure of the rock. Magnified 100 diameters.

as seen with the microscope are very sharp. It is only possible to get a few in focus at one time to photograph. Outward from these crystals is a clear ring bordered by a transitional cloudy zone grading into the opaque ring. This ring is in turn surrounded by a clear ring and the whole inclosed in opaque jasper. The crystals are interpreted as having been formed by a segregation of iron oxide from the now clear nucleus while the whole was in a gelatinous state.

The manganiferous portion of the chert from the same locality is seen in thin section to consist of a breccia of two sorts of chert. The matrix is chert containing numerous minute cracks with filled manganese oxides which give a dark color to the whole, and the fragments are clear silica whose margins appear to have been slightly stained with manganese. In these stained portions botryoidal

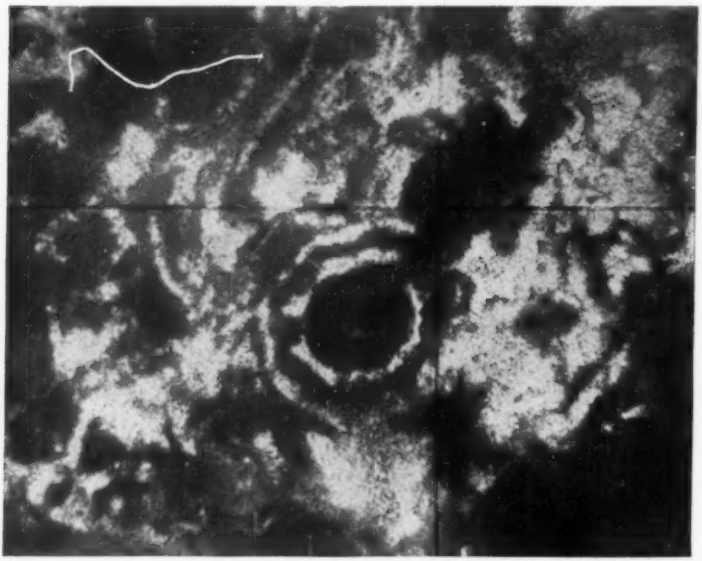

FIG. 3.—From same field as Figure 2. Shows detail of banding and dust of iron oxide included in clearer silica areas. Magnified 370 diameters.

and spherical structures are seen, both showing a faint radial arrangement of the constituent silica. In places in the clear silica fragments manganese oxides fill small irregular cracks several of which radiate from a common point and appear to indicate shrinkage.

Jasper from the interstices of the pillows on the first point west from Deepwater Point of the Northwest Arm of Fortune Harbor shows a structure very similar to that which is illustrated in Figure 2.

ORIGIN

COMPARISON WITH OTHER REGIONS

Before taking up the origin of the cherts, it will be well to compare them to similar formations elsewhere. In reading the literature of this subject, one cannot but be greatly impressed by the abundance of chert formations which are similar in many respects to those of Notre Dame Bay. Such formations have a

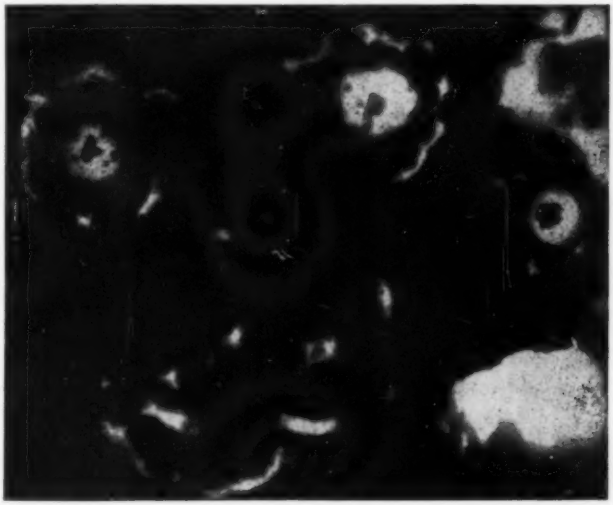

FIG. 4.—From same thin section as Figures 2 and 3. Show segregation of iron oxide into hematite plates and also original banding outside the area of segregation. Magnified 430 diameters.

very wide distribution both in area and in geologic time. E. F. Davis[1] has recently given a thorough review of the literature describing the types of chert here under discussion so that any extended review here is unnecessary. A most strikingly uniform feature of the descriptions is the intimate association with volcanic rocks. Pillow lavas usually form a part of the section, although, as in Notre Dame Bay, the chert itself is usually interbedded with shale or tuff. The following will serve as examples.

[1] E. F. Davis, "The Radiolarian Cherts of the Franciscan Group," *Bull. Univ. Calif.*, Vol. XI (1918), No. 3, pp. 235–432.

In eastern Australia is found a thick series of Devonian rocks. They form a belt extending from Tamworth to Bingara. According to David and Pittman[1] they consist principally of "clay-stones" with numerous interstratified bands of submarine tuff. There are a few limestone beds, one being 50 to 100 feet thick, and others only from 6 to 12 inches in thickness. Near Bingara and Barraba are exposed "several hundred feet of dark red-grey or greyish-white jasperoid rock" which is thin-bedded. Most of these rocks, including the limestone, are replete with radiolaria.

Near Tamworth the chert is found only in small quantities. Here there are many beds of tuff interbedded with the shale, large sections showing beds of shale alternating with the tuffs. "The shales sometimes pass into chert in contact with tuffs and cherty masses occur inclosed within the tuff beds."[2] In places there is an extraordinarily intimate mixture of chert with tuff, the chert occurring in disconnected areas of extreme irregularity.[3]

Radiolaria are found in all types of rock, cherts, shales, tuffs, and limestones, the latter yielding extremely well-preserved forms. At many places Lepidodendron remains are abundant in the shales indicating that the sediments were laid down near shore.

Analyses of various types of rock are given and in discussing these the authors say:

> With reference to these analyses, we could comment on the fact that although, so far as can be judged from the microscopic examination, the radiolarian shales are almost as rich in radiolarian remains as the black chert, the former contain only about 68 per cent of silica, while the latter contain 91.06. This points, in our opinion, to the probability that the higher percentage of silica in the chert is due, not to the silica it has received from the radiolarian tests, but rather to secondary silica derived from the siliceous tuffs.

Since the work of David and Pittman, Benson[4] has found that spilitic lava flows occur in various parts of the section. He believes that they are submarine flows and cites one instance where the lava contains coral fragments.

[1] T. W. E. David, and E. F. Pittman, "On the Paleozoic Radiolarian Rocks of New South Wales," *Quar. Jour. Geol. Soc.*, Vol. LV (1899), pp. 16–37.

[2] *Ibid.*, p. 27. [3] *Ibid.*, figure on p. 22.

[4] N. Benson, "Spilite Lavas and Radiolarian Rocks of New South Wales," *Geol. Mag.*, Decade V, Vol. X (1913), pp. 17–21.

In the southwestern part of the Kenai Peninsula, Alaska,[1] chert is found in three formations of Triassic age. The rocks are exposed on the southeast shore of Kachemak Bay, and on portions of the shore to the south.

The oldest series is composed largely of pillow lavas. It probably has a thickness of about 3,000 feet, and throughout this thickness pillow structure is well developed. In nearly every section of these rocks chert is found forming beds as much as 40 to 50 feet thick. There are in places a few thin beds of tuffs.

Younger than these pillow lavas, which cannot be referred to the Triassic with absolute certainty, is a series of rocks composed largely of thin-bedded chert. The areas of this formation as mapped "include numerous small undifferentiated masses of ellipsoidal lavas, the two kinds of rock being so intimately and complexly associated as not in all places to permit an accurate cartographic separation of the smaller areas of lava." The relations of the lava to the cherts are believed to be due in part to consecutive deposition, and in part to contiguity due to faulting.

> The cherts are everywhere intensely deformed, minute crumpling being universal and faulting being common, so that it is impossible to make even the roughest estimate of the thickness of the formation, nor can any upper and lower part be determined in any local section. . . . .
>
> The cherts are thin-bedded and even bedded rocks consisting of hard siliceous layers from half an inch to 2 inches thick, separated by thin films of softer material. The hard siliceous layers are of fairly uniform appearance except as they vary in color. They are of very fine grain, being uniformly of almost glassy texture and not containing any recognizable detrital fragments. The character of the material between the hard siliceous beds was not definitely determined, but is probably shaly. The color of the chert at most places is green, grey, or black. Brown or red cherts were noted at a few places, and are believed to owe their color to the infiltration of iron minerals. . . . .
>
> The cherts show in thin section a fine-grained siliceous groundmass containing no indication of detrital grain, but contain rounded forms which suggest the simpler Radiolaria.[2]

There is also a series of limestones whose exact relation to these other rocks is not known. They are found in the vicinity of Port

[1] G. C. Martin, B. L. Johnson, and U. S. Grant, "Geology and Mineral Resources of the Kenai Peninsula, Alaska," *Bull. U.S. Geol. Survey*, No. 587, 1915.

[2] *Ibid.*, pp. 60–61.

Graham. This series which may be about 500 feet thick contains occasional beds of tuff, tuffaceous conglomerates, and breccias. There are in the section beds of massive black chert which may be interbedded with the tuffs.

The radiolarian cherts of the Franciscan Group are unique in some respects. They have been fully described by Davis.[1] The Franciscan Group over about 1,000 miles of the Coast Ranges of California and Oregon and in the Olympic Mountains of Washington. The group shows great lithological uniformity throughout. It consists of a thick series of arkose sandstones, radiolarian cherts, and foraminiferal limestones, with subordinate shale and conglomerate. Pillow basalts and diabases are common. Some of them are believed to be intrusive. In the vicinity of San Francisco Bay there are two heavy formations of chert of 530 and 900 feet in thickness. Besides these persistent formations there are many small isolated lenses of chert, some of them outcropping over several acres. The bedding in even the thickest of these formations is exceedingly irregular, individual beds showing pinchings, swellings, and lens-like forms which are compensated for by the adjacent beds.

The radiolarian cherts of the British Isles are particularly interesting in connection with the present investigation. These cherts not only have an association almost identical to that of many of the Notre Dame Bay cherts, but some of them are contemporaneous. Moreover where fossils have been found in Notre Dame Bay they are of types so nearly identical with those of Great Britain as to imply a connection or some means of migration between the two regions.

On Mullion Island,[2] off the southwest coast of Cornwall, occur radiolarian cherts which are probably of Ordovician age, perhaps Lower Ordovician. Chert is here closely associated with pillow basalt and is found in a series of shales and limestones which are underlain and overlain by igneous rocks. The chert is interstratified with shale and occurs in bands which vary in thickness

[1] E. F. Davis, *op. cit.*, pp. 235–432.

[2] H. Fox and J. J. H. Teall, "On a Radiolarian Chert from Mullion Island," *Quar. Jour. Geol. Soc.*, Vol. XLIX (1893), pp. 211–20.

from one quarter of an inch to several inches. As many as thirty bands have been counted within three feet. The bedding of the chert is somewhat irregular, and this the authors ascribe to motion before its consolidation.

Even more striking are the Ordovician radilaria-bearing cherts of southern Scotland.[1] A continuous belt of Ordovician and Silurian rocks some 40 miles in width extends across the Southern Highlands of Scotland from coast to coast. The Ordovician rocks are best exposed in the northern part of this belt, particularly at the western extreme in the Girvan area. The lowest Ordovician is represented by a series of volcanics consisting of agglomerates, tuffs, and lava flows showing pillow structure to great perfection. In places a little chert is associated with the uppermost pillow lavas. These are overlain by a few feet of black graptolitic shale which fixes their age. Succeeding these is a series of radiolarian cherts and "mudstones," some 70 feet in thickness, which occurs sporadically over an area of about 2,000 square miles. The cherts are often interbedded with tuffs. The bedding is irregular, and in places a bed of chert may have a botryoidal upper surface. Concerning the cherts of the Girvan area the authors say:

> The volcanic series passes upwards into red, green, and gray cherts which are interstratified with tuffs and breccias that clearly overlie the Middle Arenig band of black shales. Indeed the cliff sections leave no room for doubt that the radiolarian cherts were deposited contemporaneously with the volcanic eruptions, for not only are they intercalated with the breccias, but the latter likewise contain fragments of organic chert with radiolaria, which must have solidified on the sea floor before its disruption by the explosion.[2]

The authors, following Hinde, regard these cherts as radiolarian oozes.

The Middle Ordovician or Llandeilo is conformable with the Arenig. It consists of cherts and "mudstones" with some interbedded tuffs and breccias. "In a few exceptional localities [in the northern part of the belt] the cherts are apparently intercalated with graywackes in such a way as to preclude the supposition that the relationship is due to faulting," which would indicate that if

[1] B. N. Peach and J. Horne, *The Silurian Rocks of Britain*, Vol. I, Mem. Geol. Surv. United Kingdom, 1899.

[2] *Ibid.*, p. 40.

the cherts be accumulations of radiolarian tests they can hardly be considered as oozes.

Vulcanism continued to a moderate degree into the Caradoc, but, as in Notre Dame Bay, cherts are not found in the rocks of this age. The geological history of the two regions is strikingly similar.

These examples, which might be multiplied, serve to show the wide distribution of cherts associated with volcanic rocks, and it is believed that in some instances, where volcanic rocks do not form part of the chert-bearing sections, vulcanism may have been nearly contemporaneous with the chert formation without its products appearing with the cherts. An example of such conditions is seen in the chert-bearing sections in Badger Bay of Notre Dame Bay.

Are Cherts Radiolarian Oozes?

G. J. Hinde, the foremost student of the radiolaria, regarded radiolarian cherts as lithified oozes, and continually used the presence of radiolaria as a criterion for determining the deep water origin of the rocks containing them. That the cherts are deep water deposits has often been questioned, due to the common association with black graptolitic shale, and to the occasional association with sandstones.

That the radiolarian cherts of the Franciscan Group were not deposited in extremely deep water has been shown by E. F. Davis. He says:

> The Franciscan sandstone [the principal member of the Franciscan Group] is a medium, coarse-grained sandstone which appears to be, in large part, of continental origin. None of it was laid down far below sea level. In the neighborhood of San Francisco, there are two formations of radiolarian chert which divide the sandstone into three formations. If we regard the cherts as abyssal radiolarian oozes, like those of the present day, we must believe that the region sank from sea level to a depth of from 12,000 to 15,000 feet, and that this tremendous displacement occurred twice within Franciscan time, with two reversals of movement.[1]

The association of some of the radiolarian cherts of southern Scotland with greywackes has already been noted (pp. 16–17).

[1] *Op. cit.*, p. 362.

In Notre Dame Bay the rock containing the most abundant radiolaria is not a chert but is the red shale of the islands south of Gull Island in Badger Bay.

In other occurrences of radiolarian cherts it seems that the only criterion employed for determining the abyssal origin was the presence of the radiolaria.

Have the Radiolaria Played an Active Part in the Formation of the Chert?

This question has often been raised in regard to the radiolarian cherts. It was at first answered in the affirmative, but some of the more recent investigators are inclined to the opposite opinion.

Concerning Franciscan cherts Lawson says:

> As regards the organic origin of the silica of which the chert is composed, it seems to the writer that there are features both in the slides and in the field occurrence of the formation which do not harmonize with this supposition. In the slides having the radiolarian remains, the latter generally occur as casts of forms imbedded in a matrix of silica which shows no evidence whatever of volcanic origin. The cavities of the radiolaria have been filled with chalcedonic silica, and are in definite contrast with the nonchalcedonic matrix. The discrete character of the fossils is significant of their mode of accumulation. The silica seems to have been an amorphous chemical precipitate, forming in the bottom of the ocean in which the radiolaria thrived. The dead radiolaria dropped into this precipitate, became imbedded in it, and were so preserved.[1]

Davis also holds that the radiolaria of the Franciscan cherts are merely incidental fossils which were imbedded in gelatinous silica.

In Notre Dame Bay some of the best preserved radiolaria occur in jasper. In sections of this the radiolaria appear as clear areas, sometimes showing an opaque center. The boundaries are often exceedingly sharp. The areas are composed of quartz which is relatively coarse-grained. Where radiolaria are observed in green cherts some of the silica of the chert may be amorphous. In neither case is there evidence that the rock in which the preserved radiolaria are imbedded can be in any way made up of radiolarian remains.

[1] A. C. Lawson, "Sketch of the Geology of the San Francisco Peninsula," *15th Ann. Rept., U.S. Geol. Surv.* (1895), pp. 424–25.

In this connection may be mentioned the radiolaria-free chert occurring between the interstices of pillows both in Notre Dame Bay and in pre-Cambrian areas of the Lake Superior district and on the east side of Hudson Bay.

Cherts Formed as Chemical Precipitates

The field relations and the structure as revealed by thin sections give evidence that the cherts are chemical precipitates. As to the field relations, Van Hise and Leith, in their study of the original iron-bearing formations of the Lake Superior region, have used a criterion which may be applied with equal force to the sedimentary cherts of Notre Dame Bay. This has been summarized by Leith as follows:

> The sharp contacts of iron formation rocks, the great thickness and general lack of contained chemical detritus in the iron formation, notwithstanding its association with chemical deposits, leads us to believe that the deposition of the iron formation sediments began suddenly and went on rapidly. It is not easy to conceive of the total inhibition of the deposition of fragmental sediments during this time, but relative rapidity of the deposition of the iron salts would mask the fragmental deposition. This rapidity of deposition would be more in accord with the hypothesis of rapid direct contribution of iron salts following igneous outbreak than their more slow accumulation through normal erosion processes of igneous rocks, and especially does this seem likely to be true where the iron formations completely lack associated fragmental material and are bounded both above and below by ellipsoidal flows.[1]

The silica of the cherts is very fine-grained, generally microcrystalline. In some sections there are areas in which exceedingly fine specks of faintly birefringent silica occur in an amorphous base. The occurrence of this amorphous silica is consistent with the theory that the cherts are chemical precipitates, and, as it is present in sections which show distinct radiolarian remains, it is difficult to explain as being formed of comminuted radiolarian tests.

The evidence is clear that the chert of two previously described localities at Fortune Harbor has been in a gelatinous condition. Both the jasper from the interstices between the pillows on the Northwest Arm (p. 584) and that from the heavy bed at the manganese prospect on the Southwest Arm (p. 583) show concentric rings

[1] C. K. Leith, *Lake Superior Type of Iron Ore Deposits*, in *Types of Ore Deposits*, edited by H. F. Bain, San Francisco, 1911, p. 75.

of iron-rich bands and pure silica, and the outlines of the grains of quartz of which the rock is now composed are entirely independent of this banding. Also, segregation of iron oxide into aggregates of hematite plates, the aggregate bordered by clear silica, must have taken place when the silica was in a gelatinous condition. The occasional occurrence of radiating chalcedony about these aggregates supports this view.

In connection with the concentric structures referred to above may be mentioned again the botryoidal upper surfaces of some Ordovician cherts of southern Scotland (p. 589).

Source of the Solutions

Since the conditions under which the cherts of Notre Dame Bay were formed are believed to be much the same as those under which some of the iron-bearing formations of the Lake Superior district were formed, it is of interest to examine the views of the workers in this field as to the source of the solutions. Van Hise and Leith[1] consider two sources of solutions which would produce a chemical precipitate. The first is a direct emanation from a submarine effusive. This emanation they believe to have carried a ferrous iron salt, probably the sulphate, and silicates of the alkalies. The second source of the active solutions is the reaction of the molten rock with sea water, and experiments were conducted to test the efficacy of this process. "Fresh basalts were heated in a muffle furnace to a temperature of 1,200° C., a temperature sufficient to fuse the exterior, and then plunged into salt water of the composition of sea water, the result being a violent reaction, producing principally sodium silicate but also bringing a small amount of iron into solution."[2]

The work of Dewey and Fleet[3] has an important bearing on this subject. They describe the pillow lavas of Cornwall and Devon. A peculiar feature of these rocks is that their feldspars have been extensively altered to albite, and it is shown that this took place

[1] C. R. Van Hise and C. K. Leith, "Geology of the Lake Superior Region," *Mon. No. 52, U.S. Geol. Survey.*

[2] *Ibid.*, p. 516.

[3] H. Dewey and J. S. Fleet, "On Some British Pillow-Lavas and the Rocks Associated with Them," *Geol. Mag.*, New Ser., Decade V, Vol. VIII, pp. 202–9 and 241–48.

at an early period, probably immediately after eruption. They believe that "The igneous rocks as they cooled down exhaled vapors or solutions of magmatic origin, rich in dissolved silicates of soda and other bases. These were the agencies which albitized and decomposed the lava, and any excess must have escaped into the sea water."[1] With these pillow lavas are associated cherts which carry radiolaria and the authors believe that the cherts were formed by the accumulation of their remains, pointing out that such siliceous waters would be particularly favorable to their growth.

Lawson has proposed[2] still another source for the siliceous waters from which he believes the Franciscan cherts were deposited. These cherts are not so intimately associated with volcanic rocks as are the cherts of many other regions, but pillow lavas are present in the Franciscan group. However, the evidence that these cherts have been in a gelatinous state is unusually clear, thin sections showing much isotropic silica and spherules of chalcedony. Moreover the field relations of these rocks are peculiar. "Most of the individual occurrences . . . . are of very limited extent, occupying only a few acres, or only a fraction of an acre, and it seems impossible to conceive that they had any other than a very local origin."[3] Where thick beds are found the individual members are seen to be but lenses of very limited extent. The whole aspect of the occurrences is such as to suggest a very local origin, and Lawson has proposed the theory that they are deposits from siliceous springs.

We may conclude, concerning the cherts of Notre Dame Bay, that their intimate association with volcanic rocks, as is so generally the case, indicates a genetic connection. The writer believes that they are chemical precipitates. The bedding of the sedimentary cherts is so uniform that they cannot have had such a very local origin as the Franciscan cherts. The widespread pillow lavas, usually forming part of chert-bearing sections, are considered of submarine origin. The tuffs associated with the cherts show no evidence of shallow water origin, such as ripple marks or cross bedding;

[1] *Ibid.*, p. 245.

[2] A. C. Lawson, "Sketch of the Geology of the San Francisco Peninsula," *15th Ann. Rept., U.S. Geol. Survey*, pp. 399–476.

[3] E. F. Davis, *op. cit.*, p. 245.

and other shallow water and subaerial sediments, so common in the younger formations of the district, are completely lacking. May not, then, the centers from which these tuffs were erupted have been submarine, at least in the early stages of their development? If this were the case, there cannot but have been a great contribution of magmatic waters to the basin in which the cherts were deposited.

Flows of such extent as the pillow lavas of Notre Dame Bay are generally conceded to be of fissure type, and from this source also siliceous solutions would emanate.

To a small degree siliceous solutions may have been formed by the reaction of molten rock with sea water. This would be particularly effective in the case of the pillow flows and may account for some of the silica of the chert which occurs between the pillows and which forms but a very small proportion of the whole aggregate.

Nature of Solutions and Manner of Precipitation

Some of the processes held to be effective in the precipitation of siliceous sediments may profitably be reviewed.

Van Hise and Leith have suggested the direct chemical precipitation of some of the jasper of the Lake Superior region. In their experimental work on the origin of greenalite and ferrugenous chert, they showed[1] that greenalite ($FeSiO_3$) may be formed by the reaction of a ferrous iron salt with sodium silicate as follows:

$$FeSO_4 + Na_2O.3SiO_2 = FeO.3SiO_2 + Na_2SO_4$$

and they showed that the precipitate $FeO.3SiO_2$ consists of a ferrous silicate and silica, and that the proportions of these will depend on the relative amounts of the iron salt and water glass used.

Although most of the chert of the Lake Superior region is secondary after greenalite, which may be observed in all stages of alteration to chert, they say:

> Certain facts have been described for the Keewatin iron formations indicating that the present hematitic and magnetic jaspers may not be the result of alteration of earlier ferrous compounds, but are original precipitates in the

[1] *Op. cit.*, pp. 521–22.

present form. The same kinds of solutions from these igneous rocks being postulated as seem to be required to produce greenalite and carbonate.[1]

They do not go into the details of the process of formation of the silica of the jaspers.

Davis, following Lawson, believes that the solutions which were responsible for the cherts of the Franciscan formation were derived from springs.

It is possible that a solution of silicic acid might diffuse through a fine mud on the sea floor and that the silicic acid should be precipitated throughout the mud in regular layers, thus producing the rhythmic bedding.

Perhaps a fine mud was permeated with a solution of silicic acid or some silicate, and by the diffusion of some other substance into it, ... a regular rhythmic banding was brought about.[2]

Davis performed some experiments with suspensions of clay which indicate "that silicic acid possesses the ability to free itself from mechanical impurities and that it can do so in a rhythmic manner." Thus Davis would explain the laminations of the Franciscan cherts.

Cox, Dean, and Gottschalk[3] in their work on the chert associated with the zinc ores of southwestern Missouri have thrown much light on the chemistry of silica in nature. Although their conclusions are applied to chert occurring in limestone, yet the fundamental processes which they discuss are applicable to the siliceous sediments of Notre Dame Bay.

In brief, they conclude that the silica existed in solution in ground water in the form of a colloid. This colloid they believe to have been precipitated by Ca^{++} ions formed by the disassociation of $Ca(HCO_3)_2$ which was in turn formed by the action of carbonated waters on limestone. They also indicate the possibility of some silica, as in petrified wood, being formed by the coagulative effect of positively charged colloids.

Kahlenberg and Lincoln[4] long ago investigated the nature of silica in dilute solutions. They showed that such salts as sodium

[1] *Ibid.*, p. 527.

[2] E. F. Davis, *op. cit.*, p. 401.

[3] G. H. Cox, R. S. Dean, and V. H. Gottschalk, "Studies of the Origin of Missouri Cherts and Zinc Ores," *Bull. Univ. Missouri School of Mines and Met.*, Vol. III, No. 2, 1916.

[4] Louis Kahlenberg and A. L. Lincoln, "Solutions of Silicates of the Alkalies," *Jour. Phys. Chem.*, Vol. III (1898), pp. 77–99.

silicate dissociate and yield colloidal silica. Clarke[1] in reviewing their work concludes, "in natural waters, then, silica is actually present in the colloidal state, and not in acid ions."

That silica is flocculated or precipitated by ocean water is clearly shown by its absence in the ocean water and its abundance in river water. Precipitation in this case is clearly brought about by the action of electrolites. If magmatic waters were discharged into ocean water this action would surely prove effective.

Tarr has suggested[2] a similar method of coagulation for the origin of some syngenetic chert nodules, assuming that the silica was carried into the sea by rivers. Dean[3] in criticizing this theory says:

> If, however, the silica is precipitated by the salts of the sea, these salts, or at least their cations, should be the principal material to be absorbed by silica and would hence form the principal impurity in the chert. Since sodium chloride is the salt present in largest amount in the sea water, we should expect to find a predominance of sodium in the chert; as a matter of fact, the analyses show very little sodium and a decided predominance of calcium and magnesium carbonates.[4]

In answer to this criticism it seems doubtful to the present writer if the concentration of alkalies in sea water as compared to the concentration of the alkaline earths is sufficiently high (7.3:1) to greatly overbalance the far greater coagulative power of the bivalent ions. The analysis on page 580 shows 1.04 per cent of alkalies and .73 per cent of alkali earths in molecular ratio Na+K:Mg+Ca::1.6:1. The absolute figures and the ratio appear to the writer not inconsistent with theory of coagulation by electrolites. The abundance of K is perhaps to be explained by the displacement of adsorbed Na.

It seems reasonable to suppose that the magmatic waters derived from the same sources as the volcanics of Notre Dame Bay would

[1] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Survey Bull. 616*, 1916, p. 194.

[2] W. A. Tarr, "Origin of Chert in the Burlington Limestone," *Am. Jour. Sci.*, 4th ser., Vol. XLIV (1917), pp. 409–52; "Oolites in Shale and Their Origin," *Bull. Geol. Soc. Am.*, Vol. XXIX (1918), pp. 587–600.

[3] S. Dean, "The Formation of the Missouri Cherts," *Am. Jour. Sci.*, 4th ser. Vol. XLV (1918), pp. 411–15.

[4] *Ibid.*, p. 412.

contain considerable ferrous iron. When such a solution was mixed with ocean water the iron would become oxidized and by hydrolysis ferric hydroxide would form. The iron now present in the jaspers as hematite may have been precipitated in this way. This colloidal ferric hydroxide which carries a positive charge would then be an agent which might coagulate colloidal silica and this action would be mutual.

A third process, probably of minor importance, may have been effective in the formation of the chert sediment. Van Hise and Leith, as stated above, showed that a ferrous salt will react with water glass to form ferrous silicate, silica, and a sodium salt. The ferrous silicate had the properties of greenalite. Some such reaction has very likely taken place as evidenced by the analysis of green chert which indicates the presence of both ferrous and ferric iron, and as evidenced by the occurrence of minute particles resembling thuringite in the specimen analyzed and in many others.

The danger is realized of trying to explain the exact mechanism of the chemical processes in the formation of the cherts. However, the suggestions offered above indicate methods capable of producing the materials from which the rocks could be formed. The main purpose of this paper is to call attention to the widespread occurrence of chert with marine volcanic rocks and to endeavor to establish the fact of their inorganic chemical origin.[1]

[1] Since this paper was written the paper of Gruner on the highly ferruginous cherts of the Lake Superior region has been published (*Econ. Geol.*, Vol. XVII (1922), pp. 407–60. Gruner attributes to the action of bacteria and algae the principal rôle in the precipitation of both the silica and the iron. The materials are thought to have been brought into solution largely by the weathering of volcanic rocks made more active by organic acids formed by the decay of primitive vegetal organisms. He also considers the reaction of volcanic submarine flows with water and the direct contribution of magmatic water to marine basin. Both of these sources of material he believes to be less important than by weathering products. Magmatic solutions he particularly dismisses as inadequate. Space does not permit such a discussion as the paper warrants. The present author feels, however, that there is no evidence presented which requires a change in view as to the origin of the chert of Notre Dame Bay. He has re-examined the thin sections in hope of finding some minute organisms which might have been overlooked. None were found. He believes that, if they were found, proof would be required that they were not incidental fossils as are the radiolaria.

TO QUESTION THE THEORY OF PERIODIC DIASTROPHISM

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Periodic diastrophism as it is understood by T. C. Chamberlin, R. T. Chamberlin, Schuchert, Willis, and most other writers, does not mean that diastrophism has only been locally periodic, but that periodicity has been world wide. The writer has no desire to attack the well-established idea of peneplanation and relative quiescence locally over long periods, but rather to challenge such statements as: "the earth has passed through periods of diastrophic activity alternating with periods of relative quiescence,"[1] and to replace this idea with the suggestion, that diastrophism has been continuous and that the crust has been constantly shortening to fit itself to a shrinking interior. Among American geologists the theory of periodic diastrophism is generally accepted, so that it is no small undertaking to attempt its overthrow. However, it seems to be of vital importance to a knowledge of the causes and modes of deformation of the earth's crust to know whether such deformation is continuous or intermittent. Also attempts to correlate geological time by diastrophism have been made. At least the subject should be critically examined.

In the present article periodic diastrophism will be considered from three points of view. First, a brief examination of the times of diastrophism will be made to see where the gaps, if there are any such, occur in the diastrophic record. Secondly, the apparent concentration of diastrophism at a few times during the geological history will be considered. Thirdly, the idea of accumulation of strains within the earth over long periods before yielding will be questioned.

THE GEOLOGICAL RECORD OF DIASTROPHISM

Since the conception of periodic diastrophism is based primarily on field observations, some consideration of the evidence offered by these will be made. The accompanying table has been compiled

[1] R. T. Chamberlin, "Periodicity of Paleozoic Diastrophism," *Jour. of Geol.*, Vol. XXII, p. 315.

TABLE SHOWING TIMES OF DIASTROPHIC MOVEMENTS

Geol. Time	Locality	Time Limits	Importance	References
Present	Dutch East Indies	Post-Pleistocene	Moderate	H. A. Brouwer, *Jour. of Washington Acad. of Sci.*, Vol. XII, p. 181
Pleistocene	California	Post-Pliocene during and after Saugus epoch	Great	B. L. Clark, *Jour. of Geol.*, Vol. XXIX, pp. 613–14
Pliocene and Pleistocene	Himalayas	Coarse Pliocene. Congolmerates are folded. Recent covering	Very great	R. D. Oldham, Geol. Survey, India, *Geology of India*, 2d ed., pp. 477–87
End of Pliocene	California	Post-Pliocene. Pre-Saugus	Fairly great	B. L. Clark, *op. cit.*, p. 608
Pliocene	Greater Antilles	Post-Miocene. Pre-Pleistocene	Moderate	Stephen Taber, *Jour. of Geol.*, Vol. XXX, p. 89
Early Pliocene	Caucasus Range	Post-Miocene	Great	W. B. Scott, *An Introduction to Geology*, p. 754
End of Miocene	San Francisco Region	Post-Upper Miocene. Pre-Lower Pliocene	Moderate	B. L. Clark, *op. cit.*, p. 607
Mid Miocene	Pacific Coast	Post-Lower Miocene. Pre-Upper Miocene	Great	Eliot Blackwelder, *Jour. of Geol.*, Vol. XXIV, pp. 647–48
Throughout Miocene	Alps		Great	Marcel Bertrand, *Bull. Soc. Geologique de France*, 3d ser., Vol. XV, p. 434
End of Oligocene	California Coast Range	Post-Upper Oligocene. Pre-Lower Miocene	Moderate	Ralph Arnold, *Jour. of Geol.*, Vol. XVII, p. 520
Late Oligocene	Corsica	Post-Oligocene. Pre-Lower Miocene	Moderate	Eugene Maury, *Bull. Geol. Soc. de France*, 4th ser., Vol. X, p. 290
Oligocene	Alps	Pre-Lower Miocene	Fairly important	Emile Haug, *Traité de Géologie*, II (1911), 1736
Early Oligocene or late Eocene	Colorado	Post-Bridger	Moderate	R. C. Hill, *U.S. Geol. Survey, Walsenburg Folio*, p. 2
Late Eocene and early Oligocene	Pyrenees Spain	Between mid-Eocene and late Oligocene	Important	Emile Haug, *op. cit.*, p. 1572
Middle Eocene	Alaska and parts of Rockies	Post-Lower Eocene. Pre-Neocene	Great	Brooks and Prindle, *Prof. Paper 70, U.S. Geol. Survey*, 1911, p. 117. Rowe and Wilson, *Univ. of Montana Bull. 4*, p. 62, and others
Early Eocene and Latest Cretaceous	Rocky Mountains	After Laramie, etc. Pre-Wasatch, etc.	Very great	Most Rocky Mountain Folios of the U.S. Geol. Survey and many other citations
Late Cretaceous	Western Alps	Base of Maestrichten	Moderate	Emile Haug, *op. cit.*, p. 1127
Middle Cretaceous	Pacific Coast	Post-Comanchean. Pre-Upper Cretaceous	Moderate	Eliot Blackwelder, *op. cit.*, pp. 645–46
Lower Cretaceous	New Zealand		Great	Benson, *Jour. of Geol.*, Vol. XXX, p. 6
Late Jurassic	Basin and Pacific Ranges		Great	Eliot Blackwelder, *op. cit.*, pp. 643–45
Mid Jurassic	Crimea	Post-Lower Jurassic. Pre-Upper Jurassic	Fairly important	Emile Haug, *op. cit.*, p. 1127

TABLE SHOWING TIMES OF DIASTROPHIC MOVEMENTS—*Continued*

Geol. Time	Locality	Time Limits	Importance	References
Late Triassic or early Jurassic	Northeastern United States	Post-Newark (Late Triassic)	Moderate	Hirsson and Schuchert, *Textbook of Geology*, 1915 ed., p. 820
Mid Triassic	South Africa	Post-Lowest Triassic	Slight	Ed. Suess, *The Face of the Earth*, Sollas Trans., Vol. IV, p. 102
Early Triassic	Donetz basin Russia	Post-Upper Permian. Pre-Jurassic	Moderate	Emile Haug, *op. cit.*, p. 834
Late Permian and probably partly Triassic	Appalachian Mountains	Post-Lower Permian. Pre-Late Triassic	Important	David White, *Bull. Geol. Soc. America*, Vol. XIV (1903), pp. 538–42, and many others
Lower Permian	Hercynian System Western Europe		Great	Emile Haug, *op. cit.*, pp. 917–18
Late Pennsylvanian	Hercynian System	Westphalian below, Stephanian above	Great	Emanuel Kayser, *Geologische Formationskunde*, 2d ed., p. 174
Middle Pennsylvanian	Arbuckle Mountains	Post-Mississippian. Pre-Uppermost Pennsylvanian	Moderate	J. A. Taff, *Prof. Paper 31, U.S. Geol. Survey*, p. 38
End of Mississippian	Arbuckle Mountains	Post-Mississippian. Carboniferous conglomerates above	Moderate	*Ibid.*, p. 37
Mississippian	Australia	Post-Upper Devonian Great erosion before Permo-Carboniferous	Fairly great	C. A. Sussmilch, *Geology of New South Wales*, 2d ed. (1914), p. 81
End of Devonian	Ancestral Ranges of Europe	Post-Devonian. Pre-Lower Carboniferous	Fairly great	Emile Haug, *op. cit.*, p. 831
Late Devonian	Northeast United States	Post-Hamilton. Pre-Uppermost Devonian	Fairly great	R. T. Chamberlin, *Jour. of Geol.*, Vol. XXII, pp. 330–31. J. M. Clarke, *Mem. New York Mus. No. 9* (1908), pp. 14–15
Lower or Mid Devonian	Alaska	Post-Silurian. Pre-Uppermost Devonian	Moderate	W. C. Mendenhall, *Prof. Paper 41, U.S. Geol. Survey*, p. 76
Beginning of Devonian	Caledonian Mountains, Wales		Moderate	Jukes-Browne, *Building of the British Isles* (1911), p. 114
End of Silurian	Caledonian Mountains, Scotland, and Scandinavia		Great	Ed. Suess, *op. cit.*, Vol. II, pp. 82–86, 386–89
Upper Mid Silurian	Spitzbergen	Post-Silurian undif. Pre-Uppermost Silurian	Moderate	Olaf Holtdahl (cited by R. T. Chamberlin, *op. cit.*, p. 328)
Early Mid Silurian	British Isles	Post-Lower Silurian. Pre-Upper Silurian	Moderate	A. C. Ramsay, *Physical Geog. and Geol. of Great Britain*, 6th ed. (1894), p. 74
End of Ordovician	Australia	Post-Ordovician. Pre-Silurian	Great	C. A. Sussmilch, *op. cit.*, p. 18
Late Ordovician	Appalachian region	Began pre-Richmond, probably continued into Silurian	Great	E. O. Ulrich, *Bull. Geol. Soc. Am.*, XXII (1911), pp. 436–37

to show the almost continuous record of orogenic diastrophism since the beginning of the Paleozoic. In compiling the table, pre-Cambrian diastrophic movements are not mentioned because of the great uncertainty as to the exact time of their occurrence. The table includes only a list of the most important disturbances which occurred in the different subdivisions. Several assumptions were made in compiling the table. The time of diastrophism was supposed not to be a point of time, but to have extended over a considerable fraction of a period, let us say on the average about a third of a period. This may sound arbitrary, since the length of the periods vary, but probably no harm was done in making such an assumption, because it is becoming well recognized that orogeny is not as brief a process as it was formerly considered. The orogenic disturbances in the table which are in italics were located definitely in a fraction of a period or near the juncture of two periods by taking into consideration the youngest disturbed beds and the first beds deposited after the disturbance. Since by considering these deformations alone, certain gaps were left, other orogenic disturbances the time basis of which were more open to question were used in the table. These last depend generally on the statements of reliable geologists which do not include the complete stratigraphic evidence. It can hardly be expected that the location of all these deformations will meet the requirements of everyone.

While the great warpings, which alternately submerge and emerge much of the continents, are of course considered diastrophic movements, their relation to the shortening of the earth's crust has been questioned by many. Therefore the table will not make mention of this type of deformation.

Examination of the table leads one to wonder where the great world-wide periods of quiet come in, unless they are all pre-Ordovician. While the list probably contains inaccuracies, it seems likely that there has been no time in the history of the earth, at least since the Ordovician, when there has been an absence of important orogenic movements.

PERIODIC CONCENTRATION OF DIASTROPHISM

Probably the question will have presented itself to some readers as to the possibility that diastrophism might have been continuously

active to a moderate degree, but very much concentrated at certain times. While there seems to be very little evidence that such has been the case in the Cenozoic, there is some evidence for it in the Paleozoic and perhaps in the Mesozoic. Most authors of textbooks and many other geologists speak of the end of the Paleozoic and the end of the Cretaceous as being times of very great disturbances all over the world. The end of the Ordovician, the end of Silurian, and the late Devonian are other times when diastrophism is said to have been more common than usual.[1]

In considering the probability of this type of periodicity, several points have to be borne in mind. In the first place, to have real evidence of periodicity, in each case there must be fossil-bearing horizons both directly above the unconformity and directly below. Such evidence is lacking in all but a few cases, as will be readily seen if the evidence for the times of deformation for these so-called epochs of great orogeny is examined. If the formation which is folded belongs to the next period, and if the exact horizon is unknown in each case, the deformation is generally referred with confidence to the end of the first period. If there is Silurian strata involved in folding and Devonian strata overlying the unconformity, provided that nothing is known about the exact age in either case, the deformation may have occurred well within the Silurian or even well within the Devonian period. If on the average an unconformity following mountain building represents a stratigraphic break of three-fourths of a period, the plotting of this extent of time will show that the faunas above and below the break represent different periods except when the center of the time break occurs within one-eighth of the center of the period. If the interval of the stratigraphic break is larger than this (and it generally is), the chances become still greater for discovering faunas of different periods above and below. Therefore, even if there is abundant evidence that diastrophism in many parts of the world occurred at the break in the stratigraphic record between periods, the diastrophism may have been distributed widely over the two periods.

Also, not infrequently, diastrophism is considered to have occurred directly after the close of a period when the evidence merely

[1] R. T. Chamberlin, *Jour. of Geol.*, Vol. XXXI, pp. 318–32.

shows either that the highest formations involved were located near the end of that period, or that the lowest formations not deformed belong to the next period, when the earlier record is missing. This practice is unfortunate, because the evidence merely indicates that the diastrophism occurred either after or before (as the case may be) the deposition of the beds in question and it may have occurred several periods later or previous.

R. T. Chamberlin's account of the Paleozoic disturbances[1] is very accurate and a most valuable contribution to geology, but the contemporaneity of the diastrophic movements, with which the paper deals, are based to considerable extent on the forementioned type of evidence. For example, included among the disturbances said to occur at the end of the Silurian, is one in Alaska which is based on the metamorphism of pre-Devonian rocks.[2] Again in the "Westphalo-Cardonides" deformations[3] reference is made to Haug[4] concerning certain ranges between central Siberia and South Asia. Here evidence shows only that Carboniferous formations are involved in the folding. Among the "Permo-Carbonides" deformations the folding of the Russian Geosyncline[5] is given. Concerning this Suess[6] shows that Permian strata are involved, but Jurassic is the first formation overlying the unconformity.

Since there appears to have been a general emergence of the lands at the close of the Paleozoic, it is only natural to expect that the last marine strata involved in any subsequent folding which occurred before the next marine invasion should be Carboniferous or Permian. Since any non-marine strata which may have been deposited in the meantime would probably be unfossiliferous, these would be likely to be neglected, although they might represent parts of the Triassic or later periods. Thus all post-Paleozoic and pre-Cretaceous deformations are likely to be called Permian.

Another point that must be remembered is that much of the evidence for the times of diastrophism is very inaccurate so far as

[1] *Op. cit.*, Vol. XXII, p. 315.

[2] R. T. Chamberlin, *op. cit.*, Vol. XXII, p. 326.

[3] *Ibid.*, p. 340.

[4] Emile Haug, *Traité de Géologie*, II (1911), 834.

[5] R. T. Chamberlin, *op. cit.*, Vol. XXII, p. 342.

[6] Ed. Suess, *The Face of the Earth*, Sollas Trans., Vol. I, p. 505.

the fossils are concerned because of wrong identifications and faulty interpretation of the restriction of certain species. For example, the Laramie, after which many of the Rocky Mountain deformations are supposed to have occurred, has proven to be a fictitious horizon so that it is difficult to say whether the different ranges were contemporaneous or not. The extermination of a fauna seems often to have been due to diastrophism. If diastrophism came at a somewhat different time in one part of the world than another, the faunas might change at correspondingly different times. This also might make diastrophism appear to have been contemporaneous, when it actually was not.

UNRECORDED DIASTROPHISM

Even if we consider that the evidence for diastrophism shows a greater amount of deformation at certain times during the geological history, there is good ground for doubting the validity of such evidence so far as it goes to prove that diastrophism was periodically intensified. In some parts of the geological column we find almost no traces of life, in others the remains of life are most abundant. The conclusion drawn from this evidence is not that life became almost extinct at times, but that conditions for its preservation were not as good. The same thing has probably been true of mountain building. The rapid oscillation of marine incursions have in some cases preserved the diastrophic record with more accuracy than when there were long intervals on either side of the diastrophism without marine invasions.

Various other ways in which diastrophism is likely to have occurred without leaving a record can be suggested. A few of these will be discussed.

1. *Records removed by erosion or deposition.*—If great erosion follows the development of a mountain range, it is always possible for the fossilferous beds which were involved in the folding to be removed and for pre-Cambrian metamorphics or intrusive cores to be the only remnant of a folded system. If erosion continues in the Colorado Rockies along the sides of the Front range, the upturned sedimentary rocks, which give evidence as to the time of the disturbance, may be removed leaving only a metamorphic core.

Such a range might be considered as pre-Cambrian. If deposition covers an old range, it may remain undiscovered until drill cores cut through the overlying sedimentaries. The buried granite ridges of the Mid-Continent oil fields are examples of such occurrences.

2. *Rejuvenation unrecorded.*—Most of the fairly recent mountain ranges show evidence of rejuvenation following their first uplifts. Such rejuvenation probably indicates a shortening of the earth's crust and should be considered in estimating the importance of diastrophic movements during the history of geology. It is only reasonable to suppose that the earlier ranges were also rejuvenated. Some of them are still ranges of considerable size and show undoubted rejuvenation. Usually the records of such renewed deformation are lacking. It is not unreasonable to suppose that such deformations may have helped make up for the deficiency of diastrophism during certain periods. For example, during the Cambrian where the diastrophic record is lacking, there may have been considerable deformation in the old pre-Cambrian ranges. It is even not improbable to suppose that what we consider to be pre-Cambrian folding is actually in some cases of early Paleozoic age with the disturbance involving only older sediments, either because of the local absence of the more recent sediments or because the Paleozoic present has been metamorphosed.

3. *Diastrophic records submerged.*—Since there is constant changing of the distribution of the lands, it is not unreasonable to suppose that the roots of old mountain ranges may be at present submerged beneath the sea. The old land of Appalachia is at least so buried in part. If this land supplied sediment to the Appalachian trough through much of the Paleozoic, it is likely that it was a mountainous country. The Carboniferous conglomerates of southeastern New England probably came from a land to the east of the present coast line. The thickness and coarseness of these conglomerates indicates without much question that they came from mountain ranges. Such sedimentary records have been neglected in considering the times of diastrophic movements, but they are reliable evidence of orogeny.

4. *Sub-oceanic diastrophism.*—A common fallacy among geologists is to consider that most of the orogenic diastrophism has

occurred on the continents and little of any importance on the sea bottom. Estimates of the amount of shrinkage of the globe are made by computing the amount of folding in the ranges on the lands and allowing nothing for crustal shortening beneath the seas. If the earth's interior is shrinking and the outside crust fitting itself to a smaller interior, unless the ocean bottoms show no evidence of past diastrophism, it would seem totally unreasonable to suppose that all of the shortening occurred within the lands which form such a small percentage of the total surface.

That diastrophism is going on today beneath the ocean basins is suggested by the numerous active volcanoes which occur within the confines of these basins. The location of the epi-centers of earthquakes shows more disturbance on the ocean bottoms than within the lands. To be sure, some of these earthquakes may be due to subsidence because of the weighting down of sediments derived from the lands, but much of the area disturbed is outside of the zone where continental sedimentation is occurring. On land we commonly consider vulcanism as the accompaniment of diastrophic movements. It is not altogether unreasonable to suppose that the same is true of the ocean basins.

It has been said in regard to submarine diastrophic movements that once these ranges were formed there would be nothing to put them out of existence since there is no erosion on the ocean bottom.[1] These ranges might then be thought to attain great heights and to produce great irregularities. Isostatic adjustment may have prevented the development of these ranges to very great elevations. They might go out of existence or be very much reduced in elevation either by the shifting of the zone of shortening with a resulting collapse, by the transference or cooling of a magma body beneath them, or in the other ways suggested in a previous article.[2]

Several things must be borne in mind in regard to sub-oceanic diastrophism. It would not be as concentrated as on the lands because there could be no geosynclines on the sea bottom, the irregularities produced by erosion would be missing. Diastrophism under

[1] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXII, p. 315.

[2] F. P. Shepard, "Isostasy as a Result of Earth Shrinkage," *Jour. of Geol.*, Vol. XXXI, p. 212.

the oceans would produce broad plateau-like uplifts rather than closely folded mountain ranges. Are such plateau ranges absent on the sea bottom? Unfortunately soundings of the ocean basins are not very numerous so that there is a tendency to think of the ocean bottoms as being broad flat plains without important relief. However, if we compare sections made across the Atlantic with sections across the United States giving the same number of readings in each case, we find that the sub-oceanic surface has as great major variations in contour as has the land. Figure 1 represents such a

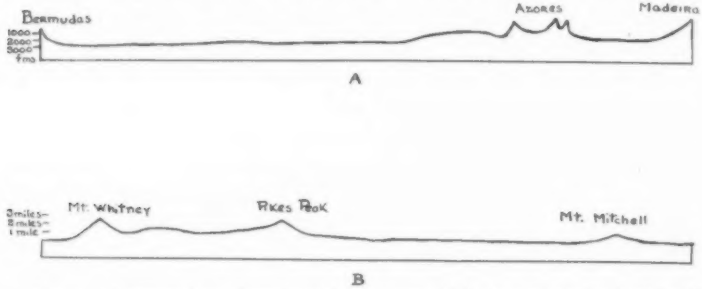

FIG. 1.—A comparison of sections with same vertical scale and similar horizontal scale giving the higher points of the Atlantic Ocean and the United States. *A*, Section of the bottom of the Atlantic Ocean. *B*, Section across the United States.

section. The data for the Atlantic ocean was obtained from soundings made by the Challenger Expedition.[1] Soundings taken recently by a United States destroyer show a more detailed section of the Atlantic,[2] which shows still greater irregularities (Fig. 2). Very likely there are great plains on the sea bottom, but these are probably only especially pronounced on the continental platform where recent deposition has evened up irregularities. Plains on the continents are more numerous than hilly surfaces. Such islands as the West and East Indies represent the higher mountain ranges of the ocean bottom.

If we can grant that there has been important diastrophism on the ocean bottom in the past, then it becomes much more difficult to prove that there has been periodic diastrophism. On the other

[1] Wyville Thompson, "Voyage of the Challenger," the *Atlantic*, Vol. I, p. 172.

[2] *Scientific American*, May, 1923, p. 330.

hand the idea of submarine diastrophism gives us a new method of strengthening the case for continuous diastrophism.

The periodic advance of epi-continental seas.—It is generally admitted among geologists that at certain times during geological history the continents were widely submerged. It is notable that such times were the occasions when diastrophic evidence is especially scarce. On the other hand, where the evidence for diastrophism is especially good, as at the end of the Paleozoic and in the late Tertiary, the continents were widely extended. There may be more significance to this occurrence than is commonly assumed.

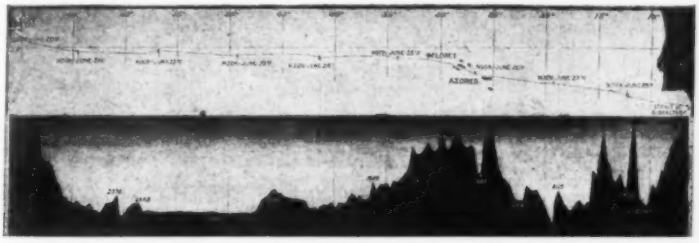

FIG. 2.—A cross-section of the ocean bottom. Vertical scale about 150 times the horizontal. (Courtesy of the *Scientific American.*)

T. C. Chamberlin explains these marine oscillations by a combination of two factors.[1] One of these is the periodic depression of the ocean basins which causes the draining of the lands and the other, the transporting of sediment out into the ocean, thus raising the sea-level, which causes submergence of the lands until there is a new depression of the sea bottom.

While the idea of the periodic depression of the ocean basins is quite commonly accepted, the basis for such an idea is difficult to discover. Presumably it is supposed that the lands are eroded and the ocean basins covered with sediment until they are so weighted that they sink under the burden. However, it must be remembered that the larger part of the oceanic basins is receiving almost no sediment, as is readily shown by the presence of Cretaceous fossils in the oceanic dredgings. Could this slow sedimentation be expected

[1] Chamberlin and Salisbury, *Geology* (1906), Vol. I, p. 57.

to cause the large variations in the sea-level in a relatively short period of time? If the evidence for the greater density of sub-oceanic material is correct, there is every reason to believe that the ocean basins owe their depth to this extra density. They should have become adjusted to this difference early in geological history, just as the earth has adjusted its oblateness to its rate of rotation. As there has been presumably little addition or subtraction from the basins, there is little reason to believe that they should have to renew this adjustment periodically. If the zones along shore sink, due to loading, the compressive effect of such shrinking would be negligible because of the narrowness of the zone.

As to the second point, let us see what the effect of erosion would be as to raising the sea-level. It must be remembered that sediments are not all carried to the ocean directly, but that there is a most important amount of deposition in the interior in river basins. Let us suppose there was a sea incursion up the Mississippi due to some slight raising of the sea-level. The Mississippi and its lower tributaries would begin to deposit in this sea and would build out the land much more rapidly than they would raise the sea-level by displacing the sea. Of course, if erosion continued long enough there would be a tendency to submerge parts of the lands, but for long periods after a great upheaval of the continents or a sinking of the sea-level the continental boundaries might be expected to be spread out rather than to retreat so far as erosion and deposition are concerned. The oscillations accompanying the advance and the retreat of the seas could hardly have been produced by the displacement of the water by sedimentation. Orogenic disturbances could easily have produced such an effect.

If diastrophism is periodic and world-wide in its effects, it is only reasonable to infer that during a disturbance there would be folding in parts of the ocean basins as well as in parts of the continents. If this were the case, the sea-level would rise and the lower parts of the continents, which were not affected by the diastrophic movements, would be submerged.

If on the other hand we consider that diastrophism has been continuous, but at some times more concentrated under the oceans and at others more concentrated within the continents, we can

explain at the same time the apparent periodicity of orogeny, if there is such, and the periodic incursions of the sea. When the ocean bottom was taking up the brunt of the shortening of the crust, the sea-level would rise in relation to the lands. Then when the chief orogenic disturbances were within the continents, the bottom of the sea would be relatively depressed and the epicontinental seas would be drained.

THEORETICAL CONSIDERATIONS

Is it not questionable whether the idea of periodic diastrophism would ever have originated had it not been for some early field evidence which suggested it? If the interior of the earth is shrinking constantly, whether at an increasing or a decreasing rate, the non-shrinking outer crust might naturally be expected to fit itself to the interior without interruption. The crust is variously computed to support from $\frac{1}{200}$ to $\frac{1}{500}$ of its own weight so that it is not reasonable to expect the rigidity of the crust to allow an open space to develop underneath due to the contraction of the interior without a wrinkling of the crust to fit it.

If the crust could store up stresses for a long period before giving away to them as suggested by Chamberlin,[1] would it not be reasonable to suppose that diastrophism would occur in only one zone after the breaking point was reached? Once one zone of weakness collapsed, the pressure on other points, where relief was apt to take place, would be reduced and a crowding toward the range where deformation had set in would be expected, while quiet prevailed elsewhere. This state of affairs is not what is looked for by the advocates of periodic diastrophism, but on the contrary they speak of a contemporaneous development of diastrophic movements in many parts of the world.

If the crust is rigid enough to store up stresses during long periods, then burdening of the crust would not be expected to cause yielding for long periods. The constant warping of the crust in many parts of the world during the present cycle suggests that the crust is rather easily disturbed from its state of equilibrium. This warping is especially significant if we agree with T. C. Chamberlin in believing that the present isostatic condition of the crust is due to

[1] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXVII (1918), p. 193.

recent world-wide movements which have removed the long accumulated strains.[1] The great glaciers which came down over Canada and northern United States appear to have caused a decided depression of the land, which is shown by the great uplifts which have occurred since the ice retreated.[2] During the formation of geosynclines there must have been subsidence at about the same rate at which the sediment was added. This suggests that the burdening due to the addition of the sediment was important enough to have some effect on the deformation of the crust. Earthquakes are said to be very common in the submarine portions of deltas offering another indication of the weakness of the crust. Also if the crust is actually in an isostatic condition in all places, it must be very weak. Thus the plea for a crust strong enough to accumulate strains through long ages and then give away with great momentum is not supported by observations.

It would be foolish to deny that the earth is rigid to stresses of short duration, but when stresses are applied over fairly long periods of time, thousands of years for example, the most rigid of bodies may yield. Experiments on the strength of material may have sufficient pressure to be compared to the forces acting beneath miles of rock, but those experiments cannot be continued long enough to give any idea of the effect of the time factor.

Crustal creep toward mountain ranges.—A point which seems to have been neglected by most geologists who believe in the shrinking of the earth, is the means by which all of the shortening of the crust is concentrated within a relatively small portion of the earth's surface, namely the mountain ranges. If a balloon is inflated and covered with paraffin and some parts of this paraffin are thinner or weaker than other parts, allowing some of the air to escape from the interior of the balloon will cause crumpling to take place in the weaker zones of the paraffin while the remainder of the paraffin slides along the surface of the balloon toward these zones of crumpling.[3] The shrinkage of the earth with the resulting development of plains and mountain ranges must be a process very similar to this.

[1] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXVII (1918), p. 197.

[2] R. A. Daly, *Bull. Geol. Soc. America*, Vol. XXXI (1920), p. 303.

[3] R. T. Chamberlin and F. P. Shepard, "Some Experiments in Folding," *Jour. of Geol.*, Vol. XXXI (1923), pp. 495–96.

If after some deformation a mountain zone becomes strong enough to resist further deformation, the parts of the crust which were sliding toward it, will start moving toward another zone of greater weakness, while deformation in the first zone may cease for a long period of time. Is it not just this change of the location of the site of deformation, rather than the cessation of movement, which has lead many to believe in the hypothesis of periodic diastrophism?

SUMMARY

Periodic diastrophism is taken to mean world-wide periodicity of orogenic movements and not local periodicity. This hypothesis appears to have three fundamental weaknesses. First, geological evidence shows a series of diastrophic movements which are almost continuous from the Ordovician to the present. Second, the belief in an excess of diastrophism at some epochs of geological time over those of other epochs is due either to the common assumption that diastrophic movements come at the end of a period, when the evidence is not sufficient to justify such conclusions; to the records of diastrophic movements having been erased at some times more than at others; to the unrecorded evidence of sub-oceanic diastrophism which probably alternates in intensity with continental diastrophism as is shown by the record of epi-continental seas; or to the shortening of the crust by minor flexures which leave no record of their time, but probably are important in amounts. Thirdly, theoretical considerations show that the idea of periodic diastrophism is contrary to what would be expected of a shrinking globe, which as geological evidence suggests has a crust that is rather easily disturbed by differences of weighting and therefore could not be expected to accumulate large strains. Further, the crust would have to support a large part of its own weight in order not to fit itself constantly to a shrinking interior and it is believed that it can support only a small fraction of its own weight.

Although admitting the possibility that future accurate studies may demonstrate that diastrophism has been periodic, it seems clear to the writer that in view of our present knowledge of the subject each of the three weaknesses cited form a serious barrier in the way of the acceptance of the hypothesis and taking them altogether there is little reason to believe in periodic diastrophism.

REVIEWS

Geology and Ore Deposits of the Yanahara Mining District, Province of Mimasaka, Japan. By TAKEO KATO. Japanese Journal of Geology and Geography, Transactions and Abstracts, Vol. I, Nos. 3–4, Tokyo, 1922, pp. 77–116, plates XIII–XVIII and text-figures 1–13.

These numbers of Volume I are devoted principally to a report in English by Professor Takeo Kato, of the University of Tokyo, on the geology and ore deposits of the Yanahara mining district, formerly a producer of oxidized iron ores, now an important producer of high-grade pyritic ores. The deposits are shown to be replacement deposits in metamorphosed rocks, both igneous and sedimentary. The presence of pyrrhotite, tourmaline and actinolite indicate high temperature conditions of formation. The mineralizing solutions, it is clear, came from the batholitic intrusions of granitic rocks common in the region.

On pages 31 to 48 a number of abstracts in English are given of geologic papers published in Japan.

E. S. B.

Bulletin of the Geological Society of China, Volume I, 1922, and Volume II, 1923. Published by the Society, Peking, China.

There has come to the Editor's desk Volumes I and II of the *Bulletin of the Geological Society of China*, published at Peking. The Geological Society of China was organized in the Library of the Geological Survey in Peking in January, 1922, with twenty-six charter members. The president of the new society is Dr. H. T. Chang, chief of the Division of Geology of the Geological Survey.

The Bulletin, published in English, is the official organ of the Society and will contain proceedings of the meetings and papers presented at the meetings either in full or in abstract. Its editor is Dr. V. K. Ting, director of the Geological Survey.

Among the longer articles in Volumes I and II dealing with problems of Chinese Geology are: "The Sinian System," by Amadeus W. Grabau, professor of petrology in the National University of Peking; "The

Tsinan Intrusive," by George B. Barbour; "The Constitution of Coal," by Chung Yu Wang, in addition to numerous shorter papers and abstracts.

E. S. B.

Revision of the Flora of the Green River Formation with Descriptions of New Species. By F. H. KNOWLTON. United States Geological Survey, Washington, *Professional Paper 131-F*, 1923. Pp. 133–76, pls. 36–40.

The Green River formation, formerly known as the Green River shales, was named and described by F. V. Hayden in 1869. He recognized it as being of purely fresh-water origin, and of middle Tertiary age. Hayden showed full appreciation of its flora and fauna, and he understood the great economic value of these shales for their oil contents.

After dropping a number of names which had been formerly adopted for the Green River flora by Lesquereux and others, Knowlton accepts a list of plants among which the following groups are represented. There are five well-marked fern types. No remains of conifers have been reported, with the exception of some pollen grains. The monocotyledons are better represented, and the best of all are the palms, of which there are three nominal forms referred to different genera. Among the dicotyledons are represented:

Salix	*Ailanthus*
Myrica	*Rhus*
Juglans	*Sapindus*
Quercus	*Ilex*
Ficus	*Rhamnus*
Brasenia	

Knowlton's inferences point toward a lowland flora which required a climate that was at least warm, and possibly bordered on subtropical. He also distinguishes an upland flora requiring unquestionably warm and temperate climatic conditions. These deductions from the floral elements are supported by the insect fauna of the Green River formation. This fauna comprises a certain element that indicates tropical surroundings, and another that indicates cool, or perhaps temperate, conditions.

A. C. N.

The Geology and Mineral Resources of the Collingwood Subdivision, Karamea Division. By M. ONGLEY and E. O. MACPHERSON. New Zealand Department of Mines, Geological Survey Branch, Bull. 25 (N.S.). Wellington, 1923.

Ammergauer Studien: I. Die Pflanzendecke in ihren Beziehungen zu den Formen des alpinen Hochgebirges. Von DR. L. LOEGEL. *II. Kare und karähnliche Formen in den Ammergauer Bergen.* Von STUDIENRAT W. STADELMANN. Mit 9 Tafeln. Ostalpine Formenstudien, Abteilung 1, Heft 5. Berlin: Gebrüder Borntraeger, 1923.

Vor Verdun. Von DR. FR. STURM. Die Kriegsschauplätze, 1914–1918, Geologisch dargestellt, Heft 4. Berlin: Gebrüder Borntraeger, 1923.

Guide to the Collection of Gemstones in the Museum of Practical Geology. By W. F. P. MCLINTOCK. 2d ed. London: Printed under the Authority of His Majesty's Stationery Office, 1923. Price 1*s.* 0*d.*, net.

Problems of the Great Barrier Reef. By H. C. RICHARDS. Queensland Geographical Journal, Vols. XXXVI–XXXVII.

Anorthoclase Basalt from Mapleton, Blackall Range, South-Eastern Queensland. Proc. Royal Soc. of Queensland, Vol. XXXIV, No. 6. Brisbane, 1922.

An Unusual Rhyolite from the Blackall Range, South-Eastern Queensland. By H. C. RICHARDS. Proc. Royal Soc. of Queensland, Vol. XXXIV, No. 11. Brisbane, 1922.

Essays on the Cenozoic of Northern China. By J. G. ANDERSSON. Memoirs of the Geological Survey of China. Series A, No. 3, March, 1923. Peking.

Bulletin of the Geological Survey of China, No. 4, October, 1922. Peking.